OPM dynamic field compensation for evoked responses

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Small remnant magnetic fields perpendicular to the measurement axis of optically pumped magnetometers (OPMs) introduce amplitude and phase errors [1]. To improve measurement precision, we developed a method for cross-axis dynamic field compensation (DFC) [2]. We evaluated DFC in recovering somatosensory responses during median nerve stimulation and applications of air pulses to fingertips. We arranged a 4x4 grid of FieldLine OPMs over somatosensory cortex. Three orthogonally fixed and centered reference OPMs placed above the grid allowed us to synthesize 1st order gradiometers. We recorded data with and without DFC in closed-loop operation. Data were band-pass filtered before computing evoked fields and time frequency representations. OPMs showed higher SNR than comparable SQUID data. With DFC, OPMs showed fewer sustained drifts and less response variability (Figure 1). Responses using DFC were more focal in the beta frequency band than those without DFC, indicating a reduction in unwanted field fluctuations (not the case for gradiometers). These results suggest that DFC will benefit OPM measurements for high resolution source localization.

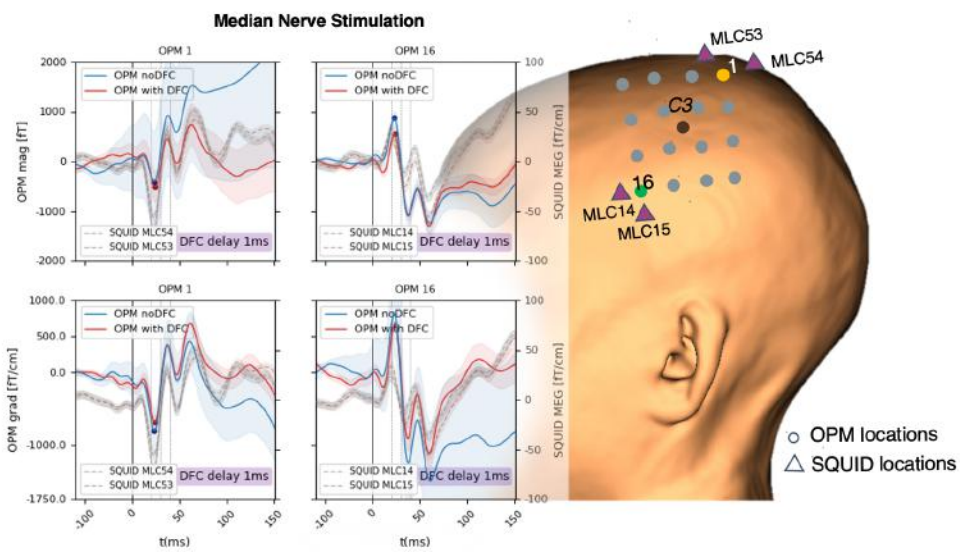

Figure 1: OPM responses to median nerve stimulation with and without DFC (red and blue, respectively). Selected SQUID MEG sensor responses are shown in gray.

References

[1] A. Borna, et al, Neuroimage, **47**(2021)
[2] S. Robinson et al, Biomag Conference (2022)

Simulation Study of the performance of an OPM-MEG system in realistic conditions

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Optically pumped magnetometers (OPMs) are a promising alternative to conventional detectors based on superconductivity. In magnetoencephalography (MEG) applications, OPMs can be placed closer to the scalp, which can lead to more accurate source reconstruction. In previous OPM-MEG system optimization studies OPM sensors are modeled either as a point in space [1] or a number of points distributed within a fixed volume with arbitrary noise levels [2]. However, the size of the sensitive volume of the OPM sensor affects not only its intrinsic sensitivity (Fig. 1) but also determines the sensitivity of the sensor to the external magnetic field. A smaller sensing volume results in higher recorded signal amplitude, but at the same time, higher recorded brain noise.

We present a model to optimize the dimensions of the sensing volume of an OPM sensor for MEG. The calculation is made for a stand-alone sensor and an array of sensors. This optimization results in dimensions that deliver the best source localization accuracy and source time course reconstruction accuracy in a realistic scenario where both, environmental noise and background brain activity, are present. We show that a change from 2 mm to 15 mm in the width of the sensing volume results in a fourfold increase in the ability to extract the time course and more than a threefold increase in localization accuracy. We also show that about 70 sensors are needed to reach full localization accuracy independent of the sensor type and size.

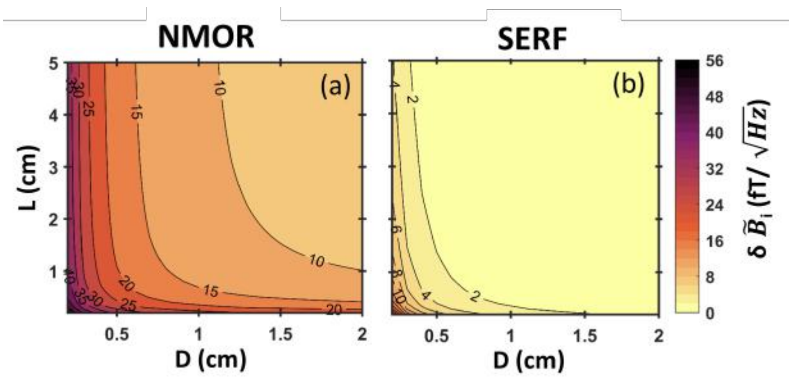

Figure 1: OPM intrinsic sensor sensitivity $\delta\tilde{B}_i$ as a function of length L and width D of the sensing volume for NMOR (a) and for SERF (b)

References

[1] E. Boto et al, PLoS ONE **11**, page **1–24** (2016).

[2] J. Iivanainen, NeuroImage **147**, page **542–553** (2017).

Concurrent EEG and OPM measurement

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With increasing dissemination of optically pumped magnetometers (OPMs), it is critical to implement largescale direct comparisons with similar state-of-the art brain imaging techniques. Considering the improved accuracy in source-localization for combined EEG and MEG recordings[1], we are performing concurrent EEG and OPM measurements, featuring 64 EEG electrodes following a standard 10-10 system and 30 OPM sensors. Furthermore, we will conduct the same recordings in the same cohort of participants, using a SQUID-MEG system.

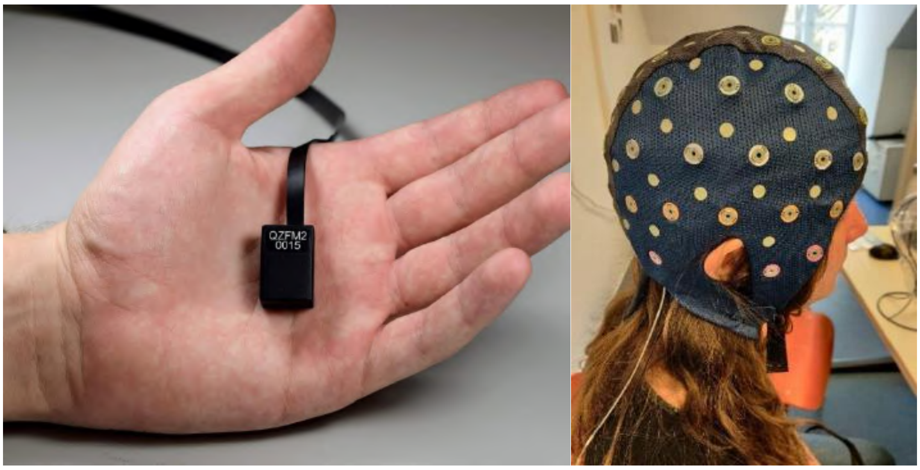

Figure 1: The concurrent EEG-OPM measure will be conducted with OPM sensors by QuSpin inc and a state-of-the-art EEG-cap with a 64-channel array by ANT Neuro inc

We will apply a battery of well-established cognitive neuroscience paradigms, recorded with more than 30 participants for direct comparison between the above methods. In doing so, we will be able to compare SNR, signal amplitude and source localization for each single methodology as well as for combined EEG-OPM. Lastly, we will research the viability of OPM-MEG towards understanding circuit dysfunctions and biomarkers in clinical settings with an additional cohort of schizophrenia patients.

References

[1] D. Sharon, M. S. Hämäläinen, R. B. Tootell, E. Halgren & J. W. Belliveau, Neuroimage **36(4)**, 1225-35 (2007).

Two-beam self-oscillating OPM for low-drift high-precision DC magnetometry

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Finite-field optical magnetometry offers practical advantages in geophysics, surveying and navigation due to the sensitivity and accuracy achievable with alkali double-resonance techniques. In this sensor scheme, resonant modulation at the Larmor frequency is applied to the alkali spins in order to drive the resonant response and maximise signal contrast [1,2]. Homodyne detection also offers a path to noise reduction in scalable electronic systems. In order to develop operating modes and readout schemes we have built a shielded laboratory magnetometer system using anti-relaxation-coated ^{133}Cs cells [3]. We will run this system as a self-oscillating spin maser as a platform for development of low-drift high-precision DC magnetometry, including study of spin dynamics and limiting noise sources.

We present developments of a two-beam optically pumped alkali magnetometer for investigation of stable Cramer-Rao-lower-bound limited magnetometry, spin-noise limited off-resonant detection of spin maser precession and long-timescale shielded optical magnetometry. We discuss potential future development of this system as a network node for new physics searches [3].

References

[1] I. M. Savukov et al., Phys. Rev, Lett. **95,** 063004 (2005)
[2] S. Groeger et al., Eur. Phys. J. D 38, 239-247 (2006)
[3] N. Castagna et al., Appl. Phys. B **96**, 763-772 (2009)
[4] S. Afach et al., Phys. Of the Dark Univ. **22**, 162-180 (2018)

Open circuit current density imaging of lithium-ion batteries using SERF OPMs

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The rapid pace of replacing fossil fuel propelled transport by electric vehicles is critically dependent on high-performance, high energy density and efficient batteries. Optimisation and safe use of existing battery cells and development of much-needed novel battery chemistries and geometries require a large range of diagnostic and monitoring tools. One such technique is current density imaging, which relies upon external mapping of the magnetic field. We extend the work in Ref. [1] to examine magnetic field features when a lithium-ion battery cell is in open circuit. An array of 2x3 SERF OPMs was placed over a battery cell to record magnetic field dynamics following charging or discharging cycles. We found that the state of charge of the battery cell affects the magnetic field profile. As a result, this technique could aid understanding of open circuit electrochemical dynamics and offers the potential to be expanded to assess state of health of the battery cell.

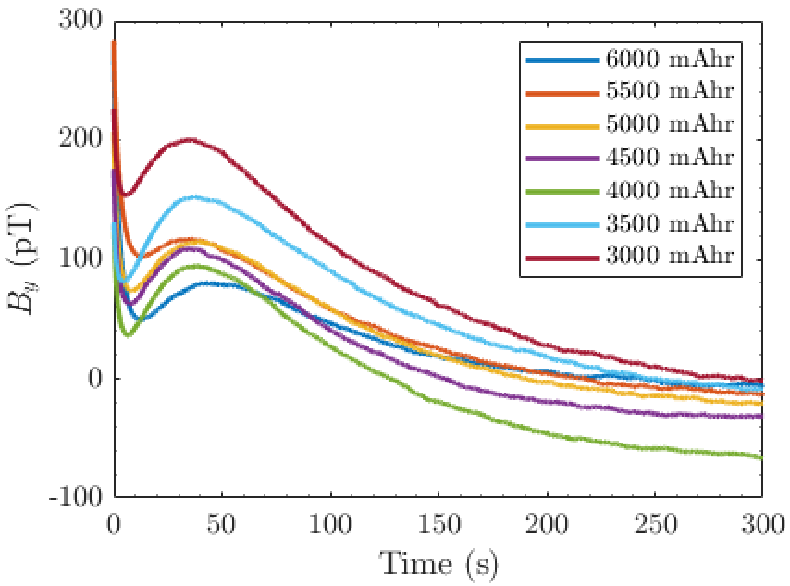

Figure 1: The magnetic field profile after a discharge cycle has finished at different states of charge for a single sensor in the 2x3 array.

References

[1] ‘Non-invasive current density imaging of lithium-ion batteries’, M. G. Bason et al., *J. Power Sources,* Vol. 533, 231312 (2022).

Fetal visual evoked responses measured with OPMs

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Fetal MEG, the magnetic signals generated by the developing brain of the human fetus, can be measured with magnetometers placed on the mother's abdomen. We attempted to measure fetal MEG responses to light flashes with OPMs.

We placed 16 FieldLine OPMs over the abdomen of a mother in week 36 of pregnancy. The measurement was made while the mother relaxed on her side on an MEG-compatible bed in a magnetically shielded room. 600 light flashes of 160 ms duration were projected onto the abdomen to elicit fetal brain responses. Both the maternal and fetal MCG were clearly evident in the raw data. The data were then averaged across trials and processed with independent components analysis (ICA) to remove the cardiograms and other artifacts. This revealed an evoked response peaking at 240 ms (Figure 1), consistent with SQUID-based fetal MEG from the literature [1]. The evoked response topography was concentrated over the lower right abdomen, consistent with the head-down fetal position that was previously confirmed with ultrasound and distinguishing it from fetal and maternal cardiac signals. To our knowledge, this is the first OPM measurement of fetal visual responses.

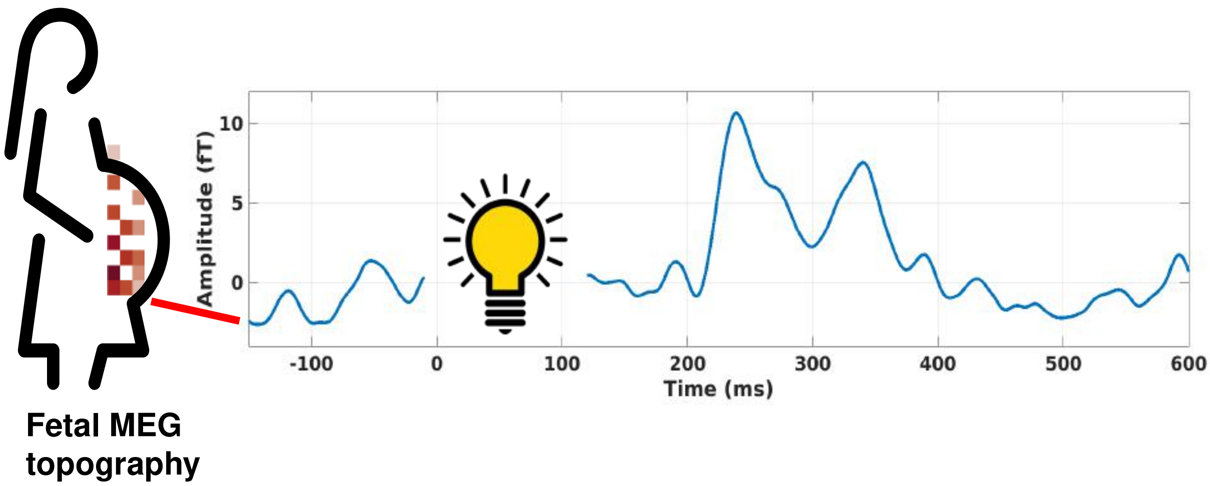

Figure 1: Fetal visual evoked response to light flashes at week 36 of pregnancy, cleaned with ICA. We believe this to be the first ever OPM measurement of a fetal visual response.

References

[1] Eswaran H et al. Exp Neurol **190 Suppl 1,** S52-8 (2004).

Compact Portable SERF Sensor for MEG

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Magnetoencephalography (MEG) is an important tool for improving our understanding, diagnosis, and treatment of brain disorders [1]. Recent developments in optically-pumped magnetometry are improving the functionality of MEG beyond traditional SQUID sensors [2]. OPMs have been shown to have comparable sensitivity to SQUIDs [3] but the small size of these devices allows significant improvement in SNR due to small standoff distance and flexible placement [4]. OPMs typically contain alkali vapour that must be heated to sufficient atomic density to enter the SERF regime, to $>150\ ^\circ$C in the case of rubidium [5]. By utilising caesium as the alkali species, an equivalent atomic density can be achieved at a lower operating temperature.

We present a portable zero-field sensor designed for use in MEG at a skin-safe operating temperature. The sensor uses a custom caesium MEMs vapour cell which operates at 120 $^\circ$C, achieving an outer package temperature of $<30\ ^\circ$C. The cell is heated using a custom low-noise and high-efficiency heater driver with temperature feedback. The sensor package is 3D printed and modular, including integrated biplanar magnetic field coils. The design of this sensor will be presented as well as preliminary results, achieving femtoTesla–level sensitivity.

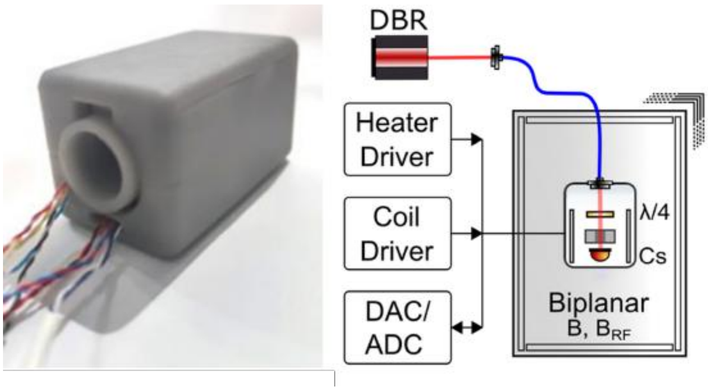

Figure 1: Left: Portable Sensor package with external dimensions of 25 x 25 x 41 mm (height, width and length respectively). Right: Experimental setup. Distributed Bragg reflector (DBR) laser (895nm), fibre coupled to portable sensor package, provides light that is polarised by a quarter waveplate ($\lambda/4$), directed through a MEMs vapour cell, and detected by a photodiode.

References

[1] S. E. Robson, NeuroImage: Clinical **12**, 869-878 (2016)
[2] E. Boto et al., Nature **555**, 657-61 (2018).
[3] I.K. Kominis et al., Nature **422**, 596 (2003)
[4] E. Boto et al., NeuroImage **149**, 404-14 (2017).
[5] K. Liu et al., IEEE (ECTC) **70**, 991-996 (2020).

A tabletop Optically Pumped Magnetometer setup for the monitoring of magnetic nanoparticle clustering with Thermal Noise Magnetometry

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Thermal Noise Magnetometry (TNM) is a recently developed magnetic nanoparticle characterization method which measures thermally induced fluctuations on the magnetic signal. It is a unique method as it maps the magnetization dynamics of the magnetic nanoparticles in an equilibrium state [1]. Such measurements have been proven to be feasible, and complementary to other characterization techniques due to their diminutive impact on the sample [2]. Moreover, the method is highly sensitive to changes in the volume of the noise sources [3] and is therefore well suited to monitor clustering processes of magnetic nanoparticles.

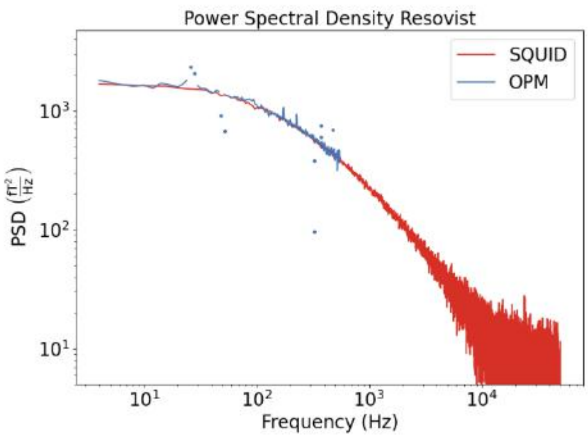

Figure 1: TNM spectra of a Resovist sample measured in the tabletop OPM setup and in an in house developed SQUID setup.

Until now, TNM measurements have only been performed with SQUID sensors because of the small signals in the fT range. In this contribution, we present a tabletop TNM setup working with commercially available OPMs (QuSpin Gen-2 Zero-Field Magnetometers) in a laboratory magnetic shielding (Twinleaf MS-2). Since our spectral measure is phase insensitive, we can use the OPMs above their manufacturer specified bandwidth by compensating for their frequency response profile in the power spectrum. A very good agreement is found between the spectra measured in the OPM setup and an in house developed SQUID system (see Fig. 1). As a proof of concept, three different clustering processes are monitored in the tabletop TNM setup and the effects on the power spectrum are presented.

References

[1] J. Leliaert et al., Appl. Phys. Lett, 222401 (2015).
[2] J. Leliaert et al., J. Phys. D: Appl. Phys., 085004 (2017).
[3] K. Everaert et al., IEEE Access, 111505 (2021).

Histogram analysis of SERF-OPM slow signal variations in different shielding environments

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Optically pumped magnetometers (OPM) are employed in many different applications such as, e.g., the study of magnetic nanoparticles [1] and the detection of magnetic fields of the human brain [2]. Although the intrinsic sensor performance is well defined by quantities such as sensitivity (noise) and bandwidth, these quantities are not necessarily sufficient to understand recorded data. Sensors need to be operated in a magnetic shield and its properties influence the observed signals. Table-top shields and walk-in magnetically shielded rooms provide orders of magnitude different suppression of external magnetic fields at frequencies below 1 Hz. A straightforward method to characterize the slow signal changes is offered by signal histograms as shown in Fig. 1. Recordings of 10 min duration (sampling rate 2 kHz) directly display the vast differences between the two types of shields. The signal fluctuations for commercial SERF-OPMs are less than 50 pT in the table-top shield (left), in the magnetically shielded room with active compensation the fluctuations reach up to 600 pT (right). In both cases, linear operation of the SERF-OPMs is guaranteed since the +-1 nT range is not exceeded. For an experiment relying on signals of interest below 1 Hz clearly the table-top shield is much better suited.

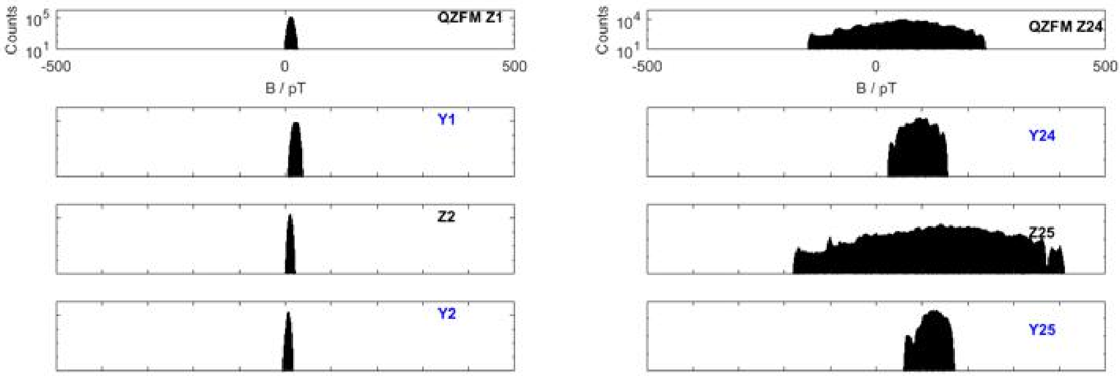

Figure 1: SERF-OPM signal histograms for (left) a 4-layer table-top shield (TwinLeaf MS-2), and (right) a two-layer magnetically shielded room with active compensation (VAC Ak3b).

References

[1] K. Everaert et al., this volume (2022).
[2] V. Jazbinšek, U. Marhl, T. Sander, (in press) in Flexible High Performance Magnetic Field Sensors, Labyt, Sander, Wakai, eds., Springer (2022).

Plants for the future with optically pumped magnetometers

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We report progress on a portfolio of experiments which employ atomic-magnetometer technology to investigate vital processes in plants. Recently, we demonstrated the detection of magnetic fields induced by action potentials in the carnivorous Venus flytrap plant [1] — a sort of “plant magnetoencephalography”, as shown in Figure 1. Current experimental efforts are focused on noninvasive magnetic monitoring of greenhouse crop plants, as well as on the development of sensors specifically tailored to measurements of plant biomagnetism. In parallel, we are pursuing studies of plant metabolic processes via molecular imaging, within the framework of zero-to-ultralow-field nuclear magnetic resonance (ZULF-NMR) [2] using OPM-based detection.

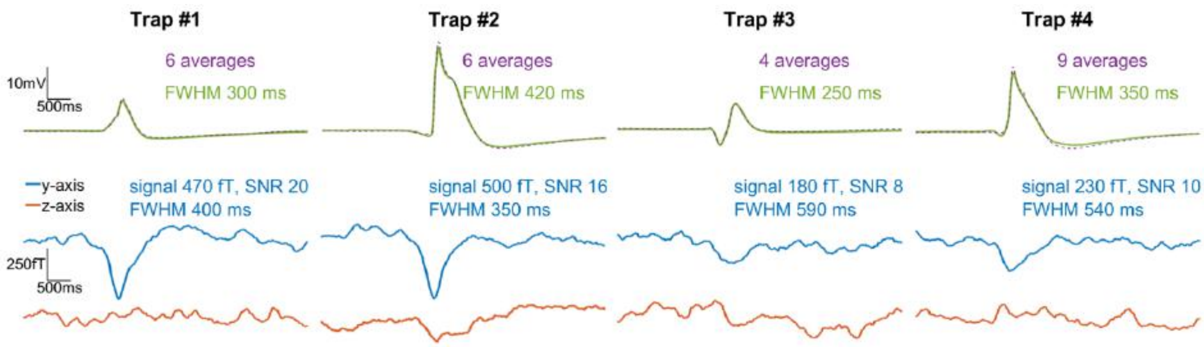

Figure 1: Electric action potentials (top) and associated magnetic signals produced by the flesh-eating traps of various Venus flytrap plants. Action potentials were induced by heat transfer and monitored using surface electrodes; magnetic fields were measured using a gradiometric OPM configuration in a magnetically shielded room. From [1].

In collaboration with international partners, we aim to develop a diverse toolbox for both fundamental research and diagnostics of plant life at the intersection of physics, biology, and chemistry. Much as atomic magnetometry is emerging as a game-changer in medicine, we believe that it also holds great promise for agriculture and ecology.

References

[1] A. Fabricant, G. Z. Iwata, S. Scherzer, L. Bougas, K. Rolfs, A. Jodko-Władzińska, J. Voigt, R. Hedrich, and D. Budker, *Sci. Rep.* **11**, 1438 (2021).

[2] J. W. Blanchard, D. Budker, and A. Trabesinger, *J. Mag. Res.* **323**, 106886 (2021).

Using OPM sensors for high-resolution MEG measurement of human gamma-band responses

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Sufficiently sensitive optically pumped magnetometers (OPMs) have become an attractive alternative to the conventionally used superconducting quantum interference devices (SQUIDs) in MEG research. As OPMs do not need a cryogenic environment to operate, they can be placed directly on the scalp, which increases signal amplitude and spatial resolution. With this improvement, weak neural activity that until now predominantly has been measured invasively could potentially also be studied with on-scalp MEG. For example, gamma-band ($\sim$30–150 Hz) activity is clearly visible in invasive recordings, whereas in non-invasive recordings only specific gamma-band responses are robustly measurable. In this study, gamma-band responses were induced in the visual cortical areas by showing ten healthy human subjects images of gratings, uniform colours and natural scenes. We measured the responses with 14 OPM sensors (QZFM gen 1 & 2, QuSpin Inc., Louisville, CO, USA) placed above the occipital part of the head. We observed that gratings and uniform colours induced narrow-band, i.e. oscillatory gamma responses, while all stimuli induced aperiodic, i.e. broad-band gamma responses. The longer-wavelength colours induced stronger responses. Thus, we were able to demonstrate that gamma-band responses – which have until now been predominantly measured invasively – can be measured with OPM-based on-scalp MEG. Yet, improvements in the sensitivity of OPMs would readily benefit this kind of studies where the factor limiting the signal-to-noise ratio is the intrinsic sensor noise rather than background brain activity or environmental interference.

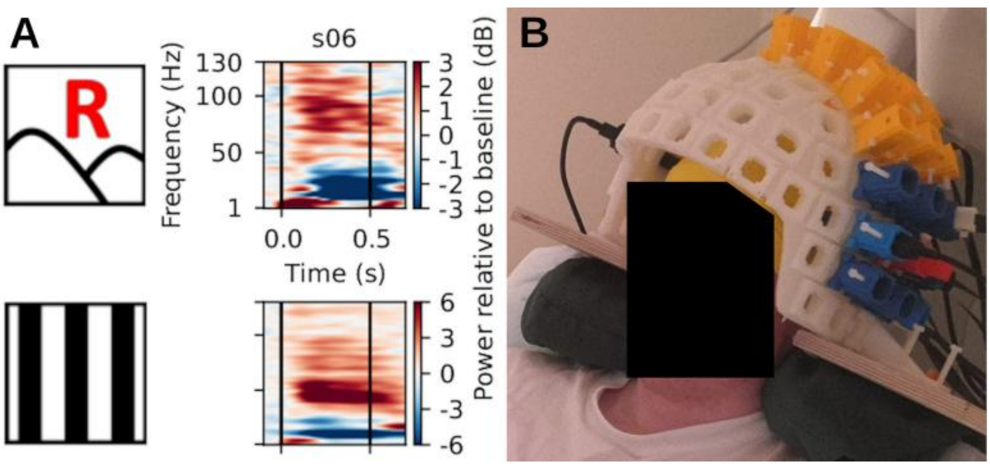

Figure 1: A. Time–frequency representations (TFRs) of the response induced by red scenes and gratings in one subject. B. Subject in experimental setup.

Bench-top magnetic field control for OPM development

P. J. Hobson[1], M. Packer[1], B. Styles[2], N. Holmes[1,3], P. Patel[2], S. Raudonyte[2], J. Chalmers[2], D. Woolger[2], A. Davis[1], C. Morley[1], D. Sims[1], M. J. Brookes[1,3], R. Bowtell[1,3], and **T. M. Fromhold[1]**

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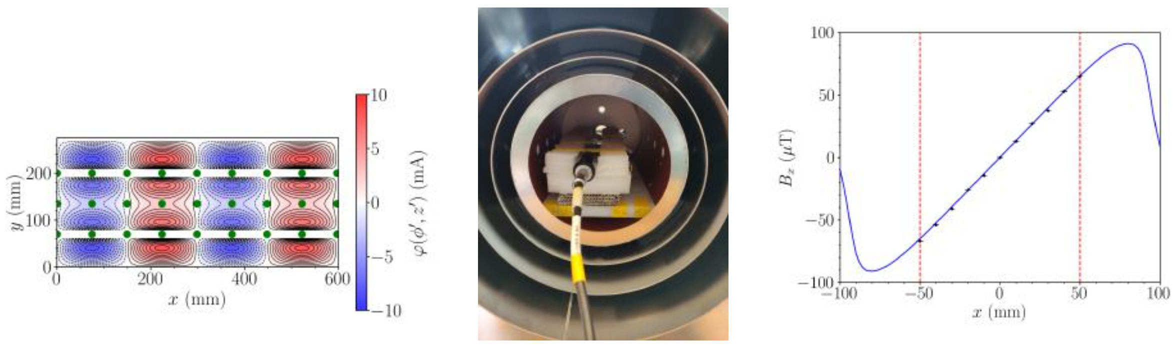

(a) (b) (c)

Figure 1: (a) Schematic of a linear transverse field gradient coil design [black solid and dashed linestyles show opposite current flow directions; red to white to blue colouring shows the value of the streamfunction from positive to zero to negative; and green circles show entry holes], which is housed on a flex-PCB of radius $\rho_c = 95$ mm and length $L_c = 270$ mm. (b) The flex-PCB is rolled inside a passive shield of inner radius $\rho_s = 100$ mm and length $L_s = 300$ mm. (c) Generated transverse magnetic field, B_x, inside the shield, versus transverse position, x, for $y = z = 0$, simulated [blue curve] and experimentally measured [black scatter]. The magnetic field is optimised between $\rho = [0, \rho_s/2]$ [dashed red lines] and $z = [-L_s/4, L_s/4]$.

Precise control of magnetic fields is essential for the development and testing of OPMs. Here, we design and characterise a bench-top magnetic field control environment for arrays of OPMs. This consists of nine nested active field-generating continuum coils housed on flex-PCBs interior to a four-layer cylindrical mu-metal passive shield of inner radius 100 mm and length 300 mm. We use a genetic algorithm to maximise the passive shielding efficiency while minimising Johnson noise and maintaining shield portability. The system is designed to control magnetic fields over half the diameter and length of the inner shield, and contains 24 transverse entry holes of radius 7.5 mm. The coil system generates nine orthogonal magnetic fields which each deviate by less than 2% over the field control region. Prototypes of the system have been manufactured, and we are preparing for final testing. The passive axial and transverse static shielding efficiencies are expected to be above 2.5×10^5 and the shield-induced Johnson noise is expected to be below 5 fT$/\sqrt{\text{Hz}}$.

The matrix coil: reconfigurable active shielding

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Movement of an OPM through the remnant field of a magnetically shielded room (MSR) induces unwanted artefacts. Active shielding, using electromagnetic coils, reduces these artefacts [2,3]. However, systems typically employ distinct coils to generate known fields over a fixed volume. Here, we describe the matrix coil, a series of unit coils with individually configurable currents to generate desired fields at any location [4,5,6]. The matrix coil consists of 48, 40-cm square, coils mounted on two planes (1.6x1.6m^2 separated by 1.7m, arranged as a 4x4 grid with an overlapping 3x3 grid, excluding central coil, Fig. 1a). 53 triaxial OPMs (QuSpin Inc.) were placed in a helmet such that the position and orientation of each sensor is known. Optical tracking (Flex13, NaturalPoint Inc.) was used to locate the OPMs in the MSR. Field data were collected, combined with the tracking data and fit to a field and gradient model. The field generated by each coil at each sensor is simulated and fit to the same model. By comparing coefficients, coil currents which compensate field changes are calculated and applied. The process repeats at 40Hz.

The artefact generated by an 'up and go' task (seated to standing, walk forward, turn 180°, return to chair and sit down, translation ~1m, 360° rotation) was reduced from ~4nT to <1nT (Fig.1b). Fig.1c shows that underlying neural oscillations from a simple finger abduction can be observed during continuously repeated up and go movements. Real-time reconfiguring of the active shielding system allows for a wider range of motion, allowing new and exciting neuroscientific experiments. However, the operational principle and insights are relevant to all types of magnetic field control.

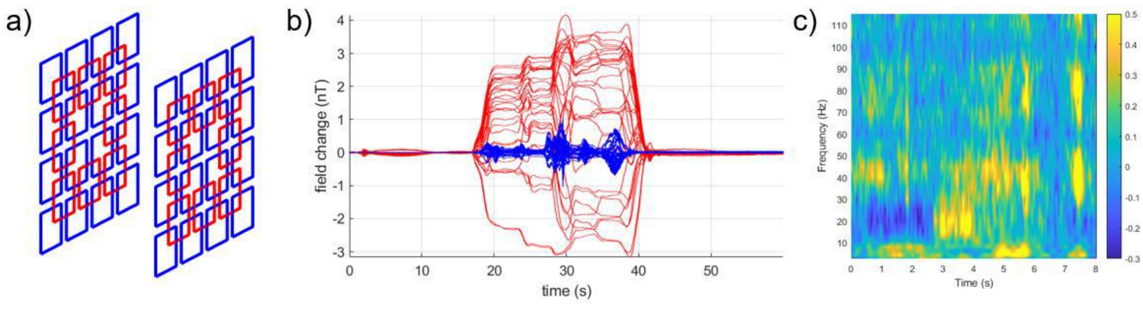

Figure 1: *a) The matrix coil (b) Time-courses of data collected by an array of OPMs during a single up and go movement, blue/red shows data with/without coils. (c) Reconstructed neural oscillations associated with left index finger abduction (0-2s) and rest (2-8s) performed during continuous movement. Source reconstruction reveals the expected movement related decrease and post-movement rebound in the beta (13-30 Hz) band. Colour-bar shows change from baseline activity.*

References: [1] N. Holmes et al., NeuroImage 2018 [3] J. Iivanainen et al., NeuroImage 2019 [4] C. Juchem et al., J. Magn. Reson. 2010 [5] A. Borna et al., Phys. Med. Biol. 2017 [6] N. Holmes et al., BioRxiv 2021

Accurate optically pumped magnetometer based on Ramsey-style interrogation

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Light–atom interactions during spin preparation and readout in optically pumped magnetometers can lead to inaccuracies. We demonstrate a novel detection strategy that exploits an interrogation sequence, analogous to Ramsey spectroscopy [1], in the pulsed free-induction-decay modality to suppress these systematic errors [2]. The technique monitors preoriented atomic spins as they evolve unperturbed during a dark interval, by subsequently applying a time-delayed optical pulse to infer the spin state's phase. The spin dynamics are reconstructed "in-the-dark" by superimposing the signals observed at various delay times. This technique could be employed in a wide variety of high-precision atomic magnetometry experiments to significantly suppress light-shift and power broadening contributions.

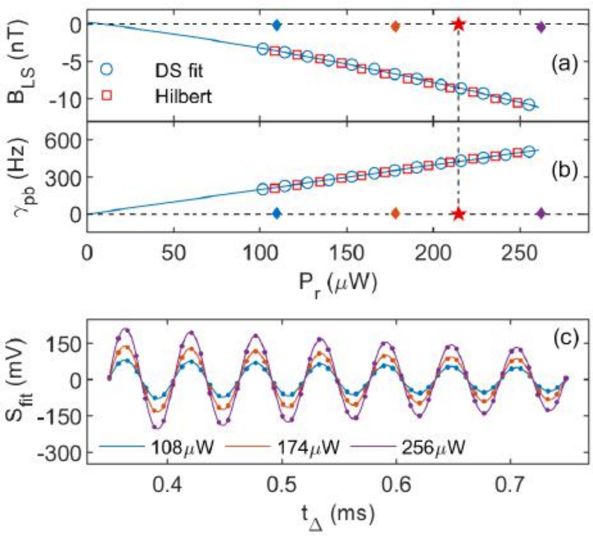

Figure 1: Suppression of (a) fictitious field B_{LS} and (b) power broadening γ_{pb} contributions using Ramsey-style interrogation. (c) Precession signals reconstructed with different readout powers. Variations in B_{LS} and γ_{pb} are represented as diamonds close to zero in (a) and (b).

Enhancements in accuracy and low drift operation are ideal for long-term magnetic field monitoring, e.g., in geophysical surveys, nEDM searches, or GPS-denied navigation. Moreover, the absence of power broadening is ideal for measuring relaxation properties intrinsic to the vapor cell with high fidelity.

References

[1] N. F. Ramsey, Phys. Rev. **78**, 695 (1950).

[2] D. Hunter, Opt. Lett. **47**, 1230-1233 (2022).

A pulsed SERF optically pumped magnetometer: Magnetic sensitivity analysis

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We have developed a pulsed optically pumped magnetometer (OPM) operating in the SERF regime [1]. The sensor prototype is based on the four-channel OPM previously developed in our lab [2]. Instead of pumping the ^{87}Rb atoms with a continuous-wave 795 nm laser, we apply short light pulses for generating a spin polarization that we measure during its free precession with an off-resonant probe beam. By applying a sequence of magnetic-field pulses, we measure a field component orthogonal to the collinear pump and probe beams (Fig. 1A). With our initial sensor implementation using a high-power laser diode integrated to the sensor head, we demonstrated sensitivity of 21 fT/rHz [1]. Here, we analyze and optimize the magnetic sensitivity of the sensor.

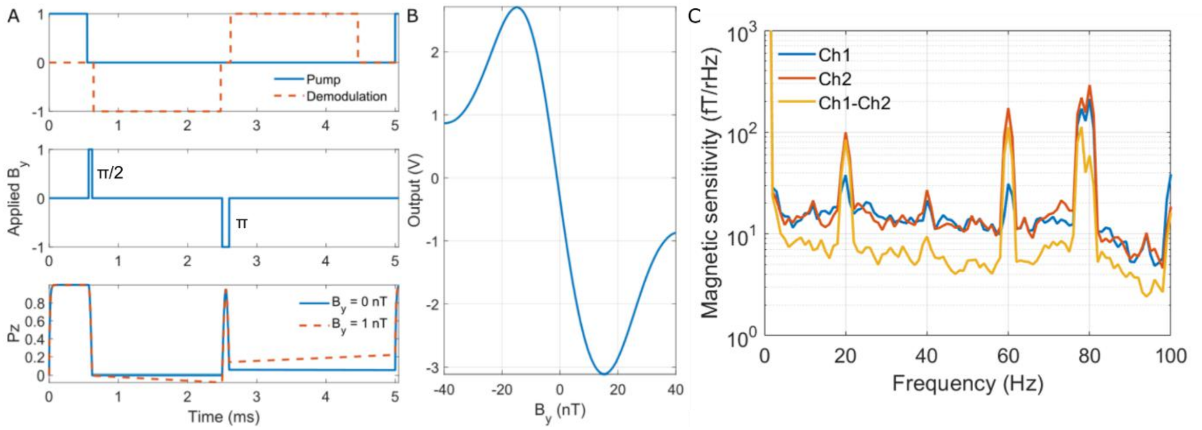

Figure 1: **A:** Pulse sequence for measuring the transverse field component B_y and the time-evolution of the spin polarization along the probe beam (P_z). **B:** The demodulation output as a function of B_y. **C:** Magnetic and gradiometric sensitivity of two channels of the sensor.

The sensor analysis shows that the sensitivity is limited by noisy optical pumping by the integrated pump laser. By using the pump laser of our MEG system [3] chopped with an acousto-optic modulator, magnetic and gradiometric sensitivities of the sensor are 14 and 6 fT/rHz, respectively (Fig. 1C).

References

[1] J. Iivanainen, 9th Workshop on Optically Pumped Magnetometers (2021).
[2] A. P. Colombo, Optics Express **24**, 15403-15416 (2016).
[3] A. Borna, Physics in Medicine and Biology **63**, 8909 (2017).

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Numerical simulation of operating condition for scalar-mode optically pumped magnetometers under the Earth's field

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Recently, biomagnetic-field measurements under the Earth's field by differential measurements with scalar-mode OPMs have been actively attempted because the method does not require extremely expensive magnetic shield rooms [1].

In this study, the performance of the scalar-mode OPMs was examined and evaluated by conducting the experiments in a shielded box. In addition, the changes of sensitivity depending on the operating condition were theoretically examined by calculating the behavior of spin polarization by numerical simulation.

As a result, the noise level obtained with the magnetometer configuration was as high as about 30 pT/Hz$^{1/2}$ in a shielded room, indicating that the system noise was dominant. Numerical simulations showed that 17.2 fT/Hz$^{1/2}$/cm^2 would be achieved by a second-order gradiometer even in a laboratory environment when the system noise in each channel was equal. From the results of the calculations, the upper limits of the repetition frequency and temperature for the sensor cell with potassium were 4 kHz and 120°C, respectively. On the other hand, the upper limits of those for the sensor cell with rubidium were 2.5 kHz and 90°C, respectively.

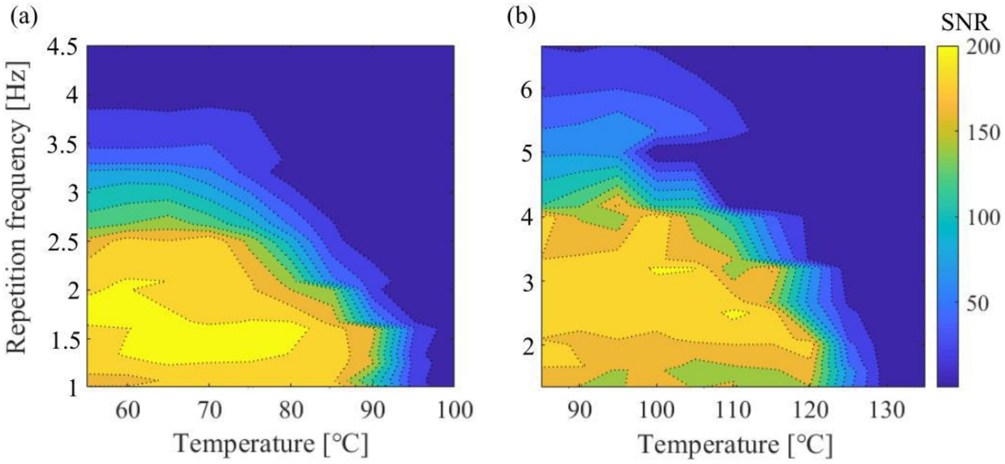

Figure 1: SNR depending on repetition frequency and cell temperature of (a) K and (b) Rb.

References

[1] M. E. Limes, *et al*., Physical Review Applied **14**(1), 11002 (2020).

Towards a commercial high-density full-head OPM-MEG system

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Magnetoencephalography (MEG) imaging with a dense array of zero-field optically-pumped magnetometers (OPMs) presents a series of challenges and opportunities. At the sensor-level, we address the stability of operating parameters such as response bandwidth, linearity, nulling, crosstalk, and scale-factor stability in a realistic hospital environment. At the system-level, we address co-registration and sensor localization challenges.

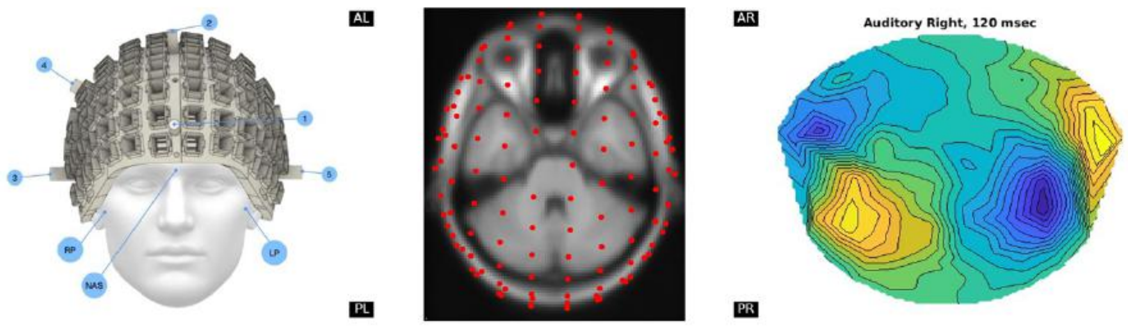

Figure 1: (left) Rendering of the OPM-MEG helmet and fiducials. (middle) Locations of the 120 OPMs overlayed on an MRI image. (right) Magnetic field map 120 ms after an auditory stimulation to the right ear of a subject.

We present results from MEG recordings with the 112-sensor system, where basic sensory-evoked field were recorded from the visual, auditory, and somatosensory cortices on a group of six healthy adults. The data was cross-validated with cryogenic MEG recordings of the same subjects.

Enhancing the sensitivity of an NMOR magnetometer

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We present the results of an increased sensitivity magnetometer based on the nonlinear magneto-optical rotation (NMOR) effect by using a repumping and multipass technique. In real--world alkali-metal atoms, with their multiplicity of ground states, the optical pumping process in atomic magnetometers is necessarily lossy [1], with a large fraction of the atoms being lost to quantum states that do not contribute to the useful magnetically sensitive signal. We use an additional repump laser with linear polarization to bring these atoms back into the useful state, shown in Figure 1(a), and thus improve the sensitivity by a factor of nearly 3 without introducing any fictitious magnetic fields associated with the repumping. Alternatively, by increasing the path length of the probe beam through our vapour cell using a multipassed optical cell, a measurement with a better signal-to-noise ratio (SNR) can be achieved. A multipass cell has been investigated in atomic magnetometers with off-resonance light [2], however, the benefits using an on-resonance probe are complicated due to the stronger light absorption. We use changes in the SNR to assess the effectiveness of multipass techniques with different probe transmissions. We demonstrate that a triple-pass cell enables an improved photon shot-noise floor of 180%, from 16 fT/$\sqrt{Hz}$ to 9 fT/$\sqrt{Hz}$ at 1 Hz shown in Figure 1(b), which agrees with the improvement in SNR.

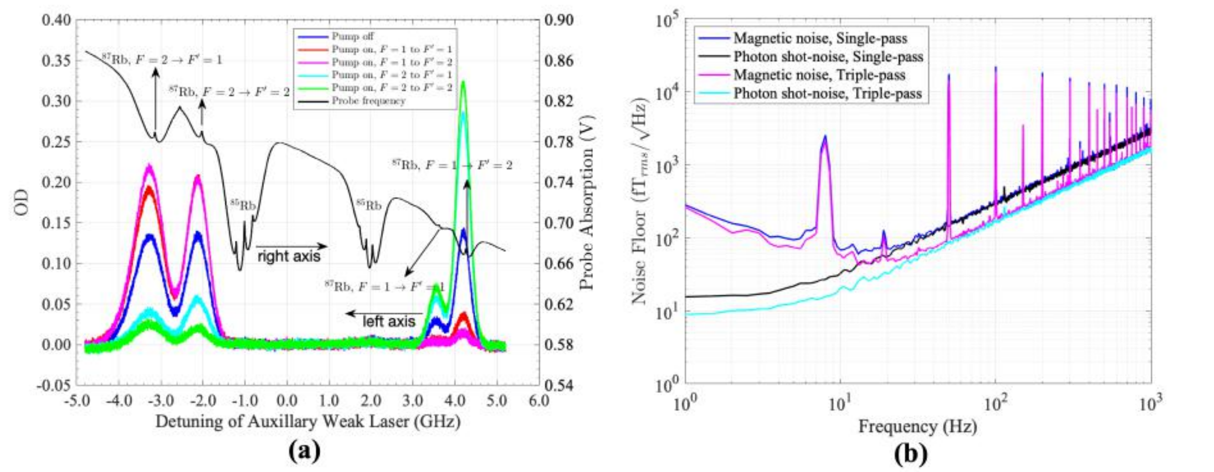

Figure 1: (a) Optical depth (OD) of ^{87}Rb atoms in the ground states under different pumping schemes and (b) sensitivity enhancement by using a triple-pass probe at a bias field of 1.5μT.

References

[1] R. Li, F. N. Baynes, A. N. Luiten, and C. Perrella, Phys. Rev. Applied **14**, 064067 (2020).

[2] V. G. Lucivero, W. Lee, N. Dural, and M. V. Romalis, Phys. Rev. Applied **15**, 014004 (2021).

Towards a whole head Helium OPM MEG system

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MEG has undergone major changes in recent years with the advent of alkali optically pumped magnetometers (OPM). These sensors, worn on the subject's head, have allowed the introduction of new experimental paradigms in MEG. Helium OPM offers an interesting alternative to alkali ones, notably thanks to their ability to operate without heating, for improved patient comfort. ^{4}He OPMs have a large dynamic range (>200 nT) and frequency bandwidth (DC-2000Hz) well suited to study all the range of brain activities. ^{4}He OPM performed more than 8 years of continuous operation in Space without noticeable ageing, in contrast with the issues reported on some rubidium OPM [1]. Currently, ^{4}He OPMs reach a sensitivity of 30 fT/rtHz in dual-axis mode [2] and work is in progress to improve further this sensitivity. We have operated these ^{4}He OPMs to record brain magnetic fields [3] in various magnetic environments, without any additional field compensation coils. Simultaneous recording with Stereo-ElectroEncephaloGraphy have been also performed to record interictal spikes [4]. Currently, a whole head MEG system with 72 to 192 channels based on He OPMs is being developped. The first recordings in real conditions are scheduled beginning of 2023.

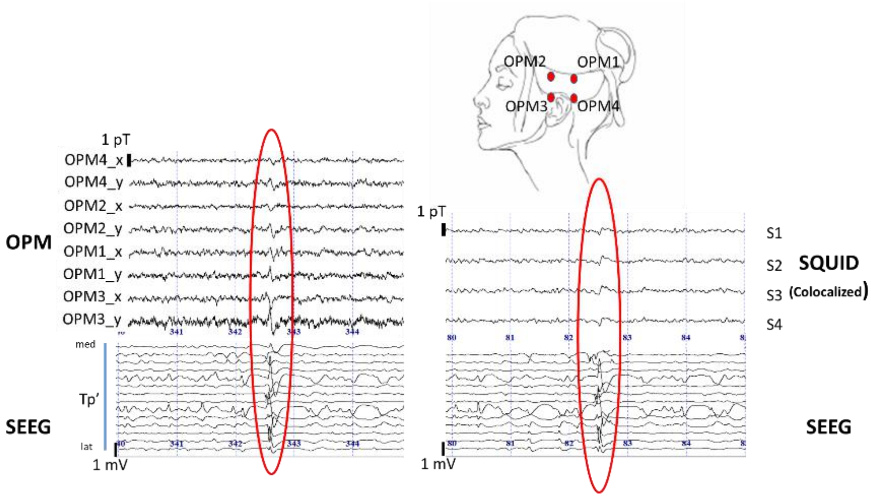

Figure 1: Simultaneous SEEG and He OPMs recording of interictal spike

References

[1] Zhi Liu *et al* 2022 *J. Phys. D: Appl. Phys.* **55** 285003

[2] Romain R, Mitryukovskiy S, Fourcault W, et al. *9th Workshop on OPM (WOPM-2021)*. Berlin, Glasgow, and Jena; 2021.

[3] Badier,JM, Bartolomei, F, Schwartz, D. et al. *Cutting EEG*. Aix en Provence; 2021.

[4] Badier J, Schwartz D, Bonini F, et al. *10th European Conference on Clinical Neuroimaging*. Geneva; 2022

Low-temperature compact atomic vector magnetometer for highly sensitive and stable weak field detection

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We demonstrate a compact low-temperature and highly stable atomic vector magnetometer for weak field measurements. As demonstrated in Fig. 1, this magnetometer, with a dimension of 78 × 78 × 78 mm^3, is assisted by two orthogonal multipass cavities. At a working temperature of 75 °C, this magnetometer shows a dynamical range of 145 nT, and sensitivities at three axes better than 55 (85) fT/Hz$^{1/2}$ at 1 (0.1) Hz. The sensor sensitivity is currently limited by the photon noise. With the diode laser free running, this magnetometer shows measurement stabilities at all three axes better than 1 pT for a measurement time of 3 hours, which is comparable with the stability of the scalar magnetometer used in nEDM experiment. This magnetometer is promising for weak field measurements that requires both high sensitivity and long-time stability.

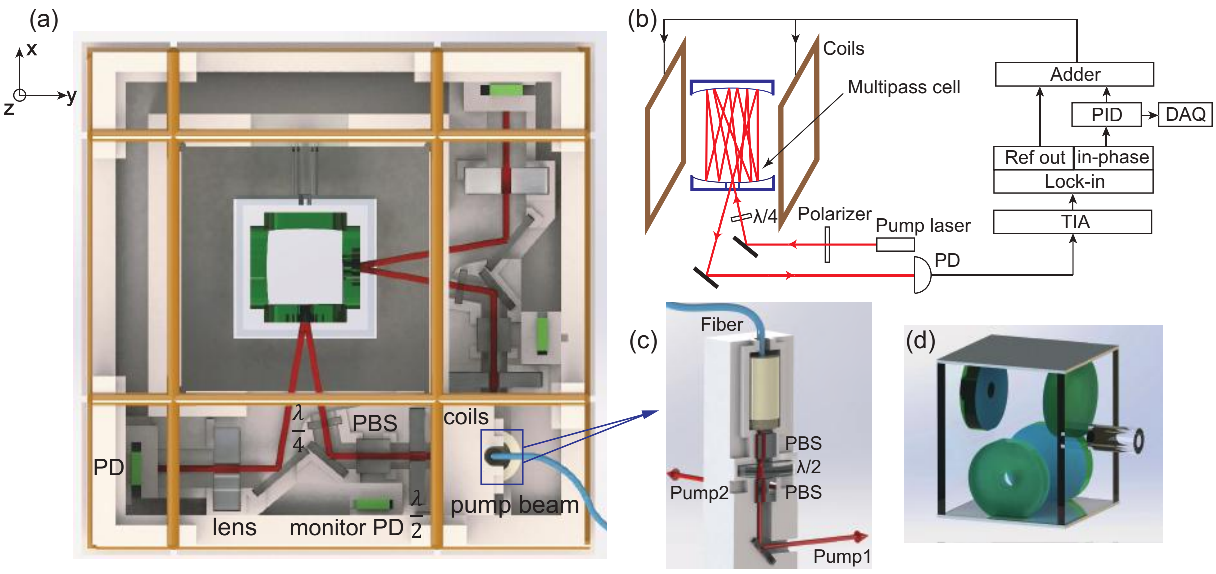

Figure 1: The vector atomic magnetometer setup.

Low-noise, high-stability VCSEL driving system

M. S. Mrozowski[1], I. C. Chalmers[1], S. J. Ingleby[1], P. F. Griffin[1], E. Riis[1]

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Optically pumped magnetometers (OPMs) have seen recent advances due to the emergence of new interrogation schemes, miniaturisation of components through MEMS vapour cell fabrication and advances in low cost laser sources[1]. Portable OPMs are especially attractive for medical applications in which they are used for detection of bio-signals. These applications include magnetocardiography (MCG)[2] and magnetoencephalography (MEG)[3]. Often, the OPMs involved are relying on fibre-coupled laser sources. Using fibres presents own set of challenges, such as vibration noise, polarisation dependence on ambient temperature and as increase in bulkiness of the system and cost. Vertical-Cavity Surface-emitting Lasers (VCSELs) offer an attractive alternative to fibre-delivered light, with their low power requirements, cost, as well as size. VCSELs are often limited by their frequency stability due to current noise as well as requiring high temperature stability (< 10 mK) at elevated temperatures.

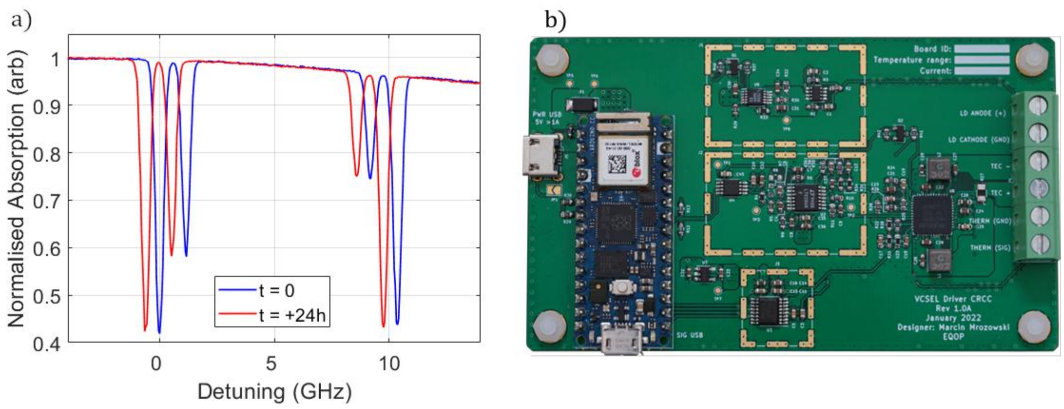

Figure 1: (a) Cs Spectroscopy 24 hour stability test. (b) Assembled device (dimension 100x60 mm) EMI shields removed to show internals.

We present a design of a compact VCSEL driving system, which consists of a highly stable, low noise current source with a nA noise performance (10 mA, 4 V compliance) and a temperature controller with ± 1 mK stability across wide temperature range of 25-80°C. The VCSEL driver exhibits a 25 MHz drift per hour which allows for operation without needing to lock the laser for many real–world applications. This driver will allow future portable OPMs to achieve better performance in designs using VCSELs.

References

[1] L. Xue et al, Applied Physics B **128**, (2022).
[2] Yang et al, Scientific Reports **11**, 5564 (2021).
[3] E. Boto et al, Nature **555**, 657-661 (2018).

Electromagnetic Induction Imaging with Atomic Magnetometers in Real-World Scenarios
A Miniaturised Sensor Taking On Present-Day Industrial Challenges

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Radio-frequency atomic magnetometers (RF-AMs) open up the potential for extreme sensitivity at low frequency in electromagnetic induction imaging (EMI). The necessity of bulky, sensitive optical and magnetic control systems in laboratory-based RF-AMs currently presents a bottleneck for this technology to emerge commercially. This talk introduces a lightweight miniaturised RF-AM package that is shown to be robust in an urban unshielded magnetic environment while undergoing mechanical translation and rotation. The sensor utilises EMI imaging to overcome specific real-world engineering problems, common to the aerospace and oil & gas industry, and offers clear advantages over existing solutions.

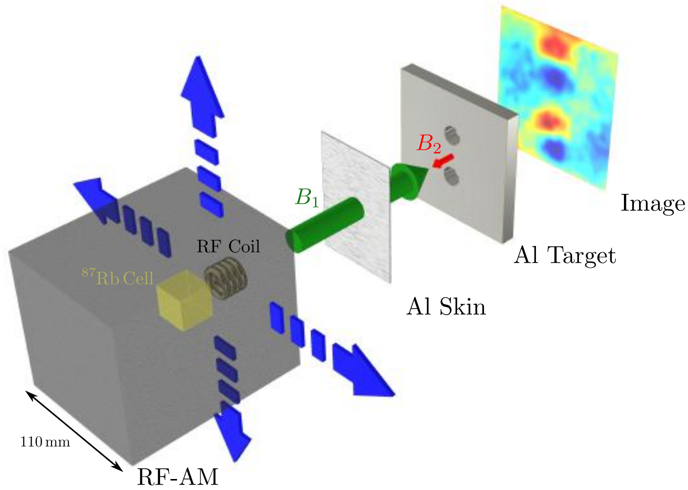

Figure 1: Illustrative depiction of the experimental geometry. A primary RF field B_1 (green arrow) penetrates the Al skin and induces a secondary response field B_2 (red arrow) in the target. The RF-AM is raster scanned across the geometry (blue arrows) building up an image of the magnetic response which reveals the structure of the target.

References

[1] Maddox B, Cohen Y, Renzoni F. *Through-skin pilot-hole detection and localization with a mechanically translatable atomic magnetometer*. **Applied Physics Letters**. 2022 Jan 3;120(1):014002.

[2] Deans C, Cohen Y, Yao H, Maddox B, Vigilante A, Renzoni F. *Electromagnetic induction imaging with a scanning radio frequency atomic magnetometer*. **Applied Physics Letters**. 2021 Jul 5;119(1):014001.

Comparing and transforming data of OPM and SQUID based MEG systems

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The use of optically pumped magnetometers (OPM) for magnetoencephalography (MEG) is already a well-established practice. Sensor locations are usually placed arbitrarily to the subject's head and are in general different from the standard SQUID MEG systems. To compare measurements made with both systems is therefore not a trivial task. In our work, we present a framework that transforms fields from one system to another [1]. The transformation approach is based on calculating an inverse solution with one MEG system and then applying it to calculate the magnetic fields on the other MEG system. We used two main source localization techniques: fitting an equivalent current dipole (ECD) and minimum norm estimate (MNE) using both realistic (BEM) and simple spherical (SPH) volume conductor models. The results show that both source localization techniques successfully transformed the measured and simulated data. Another result showed higher errors when transforming tangential components than when transforming the normal components of the OPM-MEG to the SQUID-MEG, which measures the normal component of the magnetic field only.

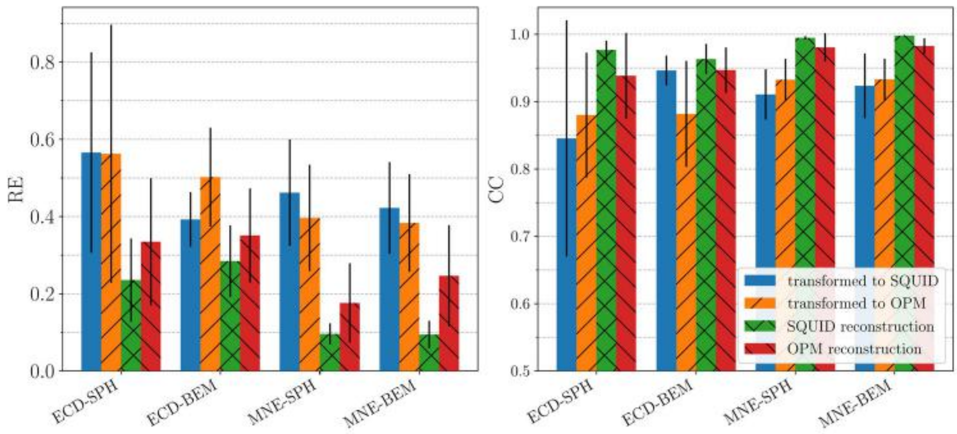

Figure 1: Comparison of transformation methods for measurements. The relative error (RE) and correlation coefficient (CC) were calculated between the measured, reconstructed and transformed magnetic field maps. The results were averaged for 8 subjects.

References

[1] U. Marhl, A. Jodko-Władzińska, R. Brühl, T. Sander, and V. Jazbinšek, PLoS ONE **17**, e0262669 (2022).

Accurate and precise magnetometry using Cs MEMS cells using a dual-beam configuration

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The free-spin-precession (FSP) optically pumped magnetometer (OPM) has the dynamic range capable of operating in magnetically unshielded conditions for real world sensing applications [1]. Exploiting the light narrowing effect [2] aids in maximising the spin polarisation, thus reducing the spin-exchange collision rate for enhanced sensitivity. Additionally, the pulsed scheme presents an advantage in accuracy over other types of OPMs due to the reduced light shifts incurred, which can be further suppressed using a Ramsey-style probe sequence [3].

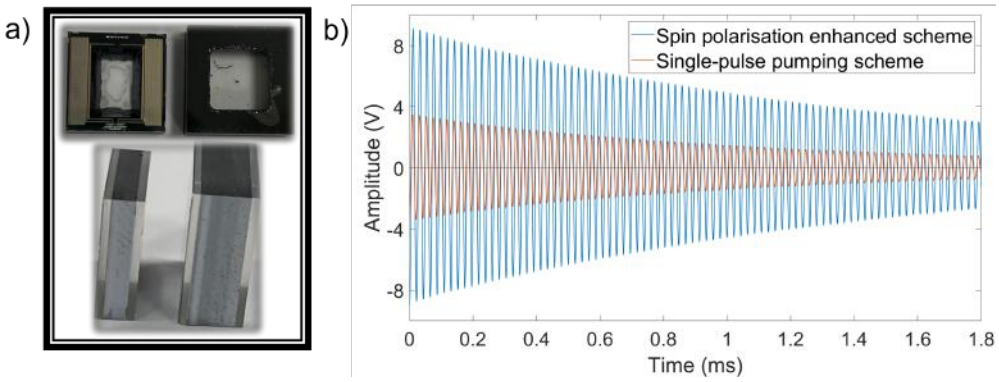

Figure 1: a) Left: previous 1.5 mm thick Cs MEMS cell fabricated at Texas Instruments. Right: 3 mm cell produced at Kelvin Nanotechnology in collaboration with UoS. b) Improved FSP signal achieved through more efficient optical pumping which enhances the spin polarisation buildup.

Here we demonstrate our FSP system leading to sub-pT/$\sqrt{\mathrm{Hz}}$ level sensitivities in finite bias fields (i.e. 50 $\mu\mathrm{T}$). This involves the use of a thicker Cs MEMS vapour cell through the fabrication capabilities (including a UoS and KNT collaboration), where the production of novel and customisable cell geometries are possible. This has resulted in a better sensitivity through improved SNRs, and longer spin coherence times. Furthermore, we discuss the transition to a dual laser pump-probe scheme, and methods of increasing the induced atomic spin polarisation to significantly improve the sensor sensitivity and dynamic range.

References

[1] M. E. Limes et al, Phys. Rev. Applied **14**, 011002 (2020).
[2] T. Scholtes et al, Phys. Rev. Applied **84**, 043416 (2012).
[3] D. Hunter et al, Optics Letters **47**, 1230-1233 (2022).

Rabi Vector Magnetometry Implemented with Hot Alkali Vapor

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Optically pumped magnetometers (OPMs) are currently used in a variety of applications ranging from biomagnetism and medicine, to geophysical surveys and tests of fundamental physics. Furthermore, many of these applications require full knowledge of the magnetic field direction. Traditionally, magnetic field direction is measured with respect to mechanical references such as a 3D laser beam system or a coil system. However, these references are subject to drifts and imperfections due to mechanical tolerances that limit the long-term vector accuracy. In this work, we demonstrate a novel approach to vector sensing with an OPM by utilizing a microwave polarization ellipse (MPE) as an accurate 3D reference.

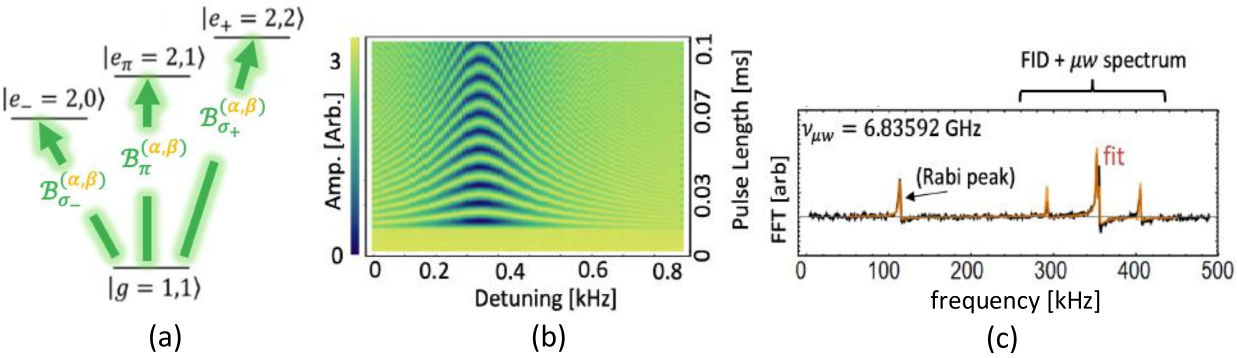

Figure 1: (a) MPE drives Rabi oscillations between $F = 2$ and $F = 1$ hyperfine manifolds. $B_{\sigma+}$, B_π and $B_{\sigma-}$ depend on direction (α, β) of DC magnetic field. (b) Chevron Rabi pattern of $\sigma+$ transition. (c) Fit to the combined Larmor FID + microwave spectrum.

We use a heated micro-fabricated vapor cell containing ^{87}Rb with N_2 buffer gas embedded in a microwave cavity for our measurements. Compared to our previous proof-of-principle experiment with cold atoms [1], this platform offers much higher sensitivity. The microwave field drives Rabi oscillations between $|F = 1, 1\rangle$ and $|F = 2, m\rangle$ (m = 0,1,2) states of the ground state manifold. The DC magnetic field direction, which determines the $\sigma+$, π and $\sigma-$ microwave components (fig. 1a), can then be extracted by either directly measuring the Rabi frequencies associated with these components or by fitting to sidebands in the Larmor free-induction-decay (FID) spectrum (fig. 1c). We use Faraday rotation of far-detuned probe beam followed by balanced photodetection for both Rabi and Larmor FID measurements. By combining an extensive theoretical model with these measurements, we have also characterized vapor cell parameters such as buffer gas pressure and cell temperature.

References

[1] T. Thiele, Y. Lin, M. O. Brown, and C. A. Regal, Phys. Rev. Lett. **121** 153202 (2018).

Co-magnetometry in Rb-Ne high pressure cells

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A long spin coherence time of alkali-metal vapors and noble gas brings an opportunity of using these ensembles for co-magnetometry, precession sensing, search for novel physics, and quantum information [1]. We have developed a co-magnetometer setup where a Rubidium vapor is kept in a glass cell with a high-pressure buffer gas consisting of Neon and Nitrogen, inside a 4-layer magnetic shield. The setup is arranged in a Bell Bloom configuration [2]. Due to the presence of the buffer gas the atomic thermal motion of the alkali atoms becomes diffusive. In a regime of relatively weak diffusion, we have detected and investigated the multimode evolution of the collective spin [3]. In particular, preliminary measurements have shown a non-trivial dependence of the different collective spin modes on the pump power. Our findings are of interest for the optimization of a large class of alkali-metal-noble-gas co-magnetometers.

References

[1] D. Budker and M. Romalis, Nat. Phys. 3, 227 (2007).
[2] W. E. Bell and A. L. Bloom, Phys. Rev. Lett. 6, 280 (1961).
[3] R. Shaham, O. Katz, and O. Firstenber, Phys. Rev A 102, 012822 (2020).

Compact method for multidirectional detection of magnetic field in atomic Cs

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Here we present theoretical and experimental magnetooptical signals based on the interaction of aligned atomic angular momentum with an external magnetic field in atomic Cs at room temperature. The excitation and observation geometry, based on [1], involves two beams, but requires only a single port for access of both pump and probe beams making the experimental setup compact. The system is pumped by linearly polarized Cs D1 laser along *x*-axis and simultaneously probed by another low intensity linearly polarized beam in the *xy* plane (See Fig. 1) originating from the same laser source, the external magnetic field is applied along the *z*-axis. By implementing the geometry from [1] it is also possible to detect the magnetic field along *x*-axis by rotating the polarization of the probe beam by 60° around the probe beam path $\mathbf{k}_S$. The turning of the probe beam polarization can be realized by an electrooptical modulator, thus enabling the detection of two orthogonal components of the external magnetic field from a single experiment. We have performed simulations of the absorption signals for various Cs D1 transitions and studied how the signal is dependent on the Rabi frequency. We have also obtained experimental signals with several combinations of pump and probe beam intensity ratios for all Cs D1 hyperfine transitions.

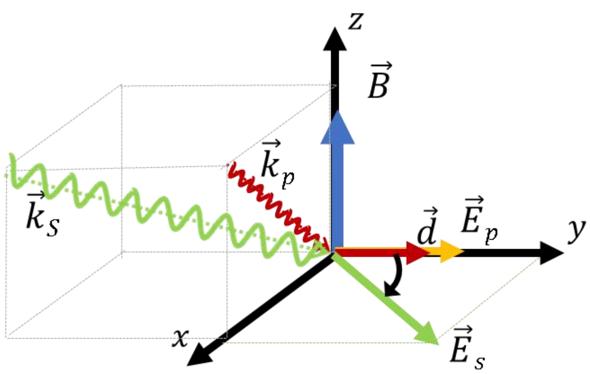

Figure 1: Excitation geometry for the detection of a single magnetic field component.

We acknowledge the support from the Latvian Council of Science, project No. lzp-2020/1-0180: “Compact 3-D magnetometry in Cs atomic vapor at room temperature”

References

[1] G. Le Gal, G. Lieb, F. Beato, T. Jager, H. Gilles, and A. Palacios-Laloy, Phys. Rev. Appl. **12**, 064010 (2019).

Towards an optically pumped magnetometer for biomagnetism in space

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[2] Institut für Physik, Humboldt-Universität zu Berlin, Berlin, Germany
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Evaluation of neuromuscular degeneration in astronauts represents a field, where conventional neurophysiological methods such as surface or needle electromyography (EMG) are not sufficient, resource consuming or too harmful. Here, easy-to-handle, flexible and robust optically pumped magnetometers (OPMs) have an unique opportunity to provide information for regular assessment of the muscles without direct medical supervision and with a performance that goes beyond surface EMG. Biomagnetic measurements with OPMs as for instance magnetomyography (MMG) are though typically performed in research laboratories and clinical facilities, providing optimal magnetically shielded environment and stable measurement conditions [1]. While the anticipated magnetic shielding in space (e.g. on the International Space Station) is practically impossible, such sensors have to comply with perturbations and the strongly varying ambient field onboard the spacecraft. Despite that, they must feature suitable performance in terms of sensitivity, bandwidth, and spatial resolution as well as secure long-term unserviced operation.

To this end, we currently explore concepts to develop robust and compact vapor-cell based devices using microintegration techniques [2] and automated frequency locking [3], to be capable to detect medically-relevant MMG signals of the leg and arm muscles in the above mentioned harsh environments. We demonstrate the performance of our functional lab-scale prototype and describe the technological road-map for conversion to space-compatible sensors.

References

[1] D. Sometti *et al.*, Muscle Fatigue Revisited – Insights From Optically Pumped Magnetometers, Frontiers in Physiology **12**, Article 724755 (2021).

[2] A. Strangfeld *et al.*, Prototype of a compact rubidium-based optical frequency reference for operation on nanosatellites, J. Opt. Soc. Am. B **38**, 1885-1891 (2021).

[3] B. Wiegand *et al.*, Linien: A versatile, user-friendly, open-source FPGA-based tool for frequency stabilization and spectroscopy parameter optimization, arXiv:2203.02947 (2022).

The advantages of triaxial OPMs for reconstructing MEG data in the presence of interference

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Developments in OPM design have enabled the introduction of 'triaxial' sensors, however, the extent to which such developments are advantageous for magnetoencephalography (MEG) remains to be seen. Recent theoretical work [1] suggests that a MEG array with triaxial sensitivity enables better rejection of interference present in MEG data due to external sources. Here we aim to verify this experimentally. Two participants each took part in four experiments, in which MEG data (during a handwriting task) were recorded in the presence of a known artefact that occurs at 16.6 Hz. These MEG data were reconstructed using a scalar linearly constrained minimum variance beamformer, using either single axis (oriented radial to the head surface) or triaxial sensitivity. Results showed that the artefact clearly visible at the sensor level was still present following reconstruction when using only the radial axes of the OPM array. After triaxial reconstruction, however, the effect of the artefact became negligible. These data therefore demonstrate the advantages of triaxial sensitivity for MEG data collection.

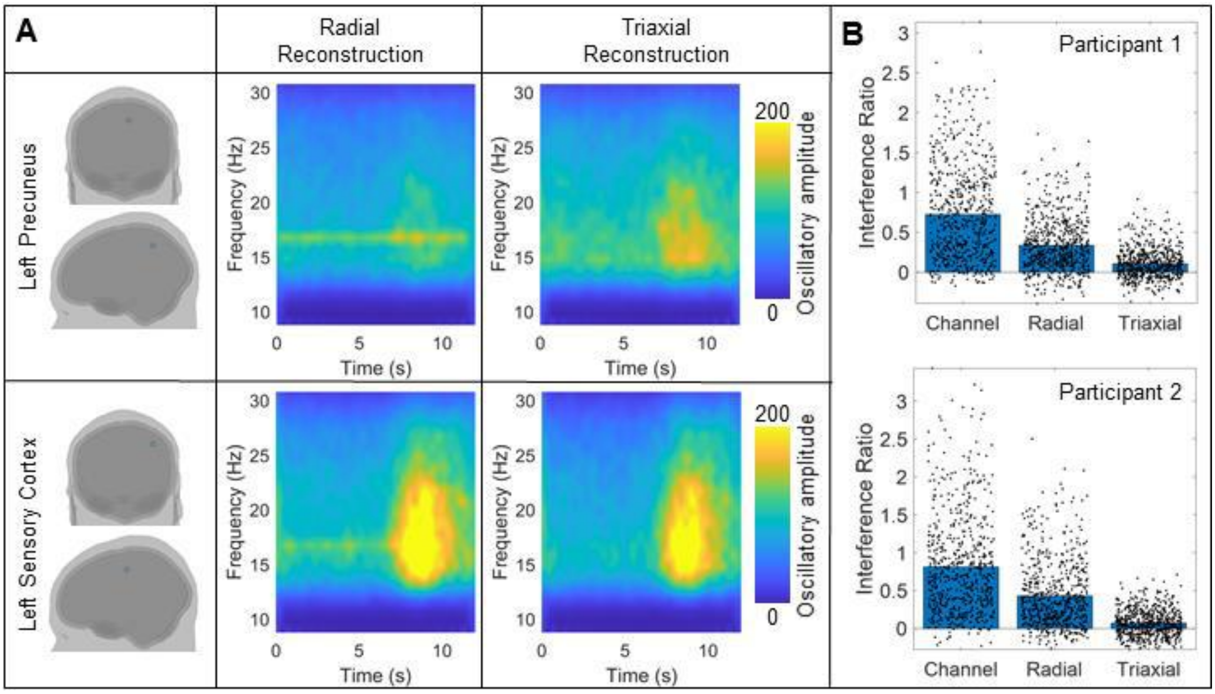

Figure 1 - A) Example time-frequency spectra showing data reconstructed using radial axis or triaxial reconstruction, in the left precuneus (above) and left sensory cortex (below) of participant 2. B) Magnitude of the 16.6 Hz artefact at the sensor level (left) and after using radial (centre) and triaxial (right) reconstruction, for both participants.

References

[1] Brookes et al, NeuroImage, **236**, 2021

Simulating coregistration of on-scalp OPM sensor arrays with two tri-axial magnetic dipoles

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For effective magnetoencephalography (MEG) measurements, the location and orientation of sensors relative to the head must be known with high accuracy. Previously this has been enabled via rigid (3D printed) helmets and/or 3D optical cameras [1]. Here, we simulate a new coregistration technique based on measurement of magnetic fields from two triaxial magnetic dipoles [2]. We simulate oscillating magnetic fields at known currents for each of the six coil loops, and fields are measured by a 64–sensor triaxial OPM array. By searching for the minimum difference between the estimated data (i.e. where we guess the sensor locations/orientations) and 'real' data, we were able to derive the locations and orientations of the sensors [3]. Sensor location and orientation errors were 0.002 mm and 0.003° respectively. However, introducing small errors in dipole location/orientation results in larger errors in sensor coregistration, with e.g. sensor position errors varying from 2 – 6 mm with a 2° uncertainty in dipole coregistration w.r.t the head. Results suggest this scheme could enable accurate coregistration of flexible OPM arrays, but results are highly dependent on dipole localisation.

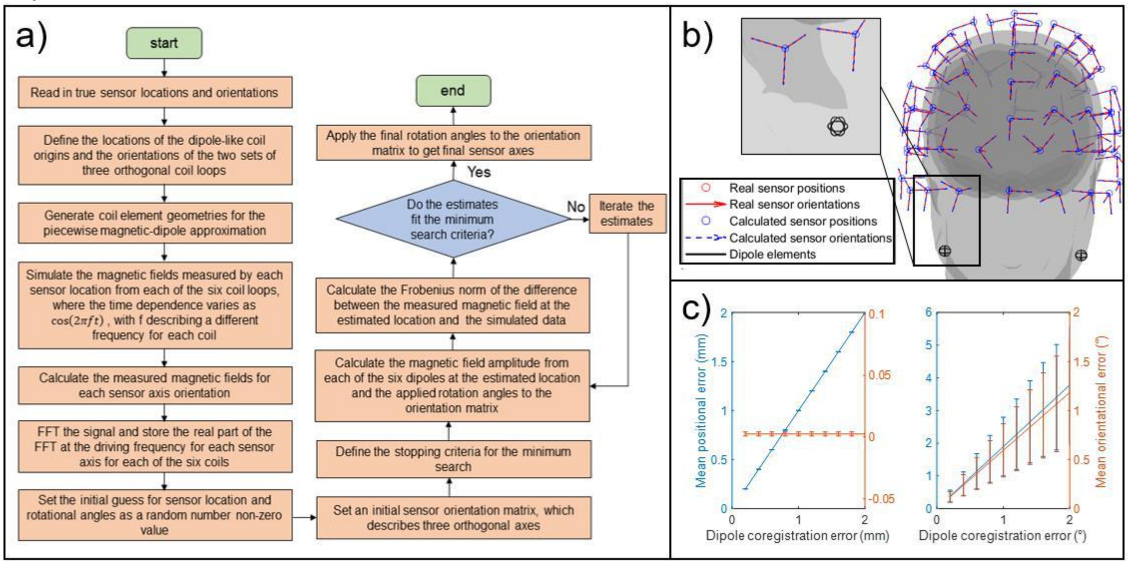

Figure 1. Figure 1a) flowchart describing how the algorithm determines sensor location and axes from simulated data. b) example co-registration on an MRI mesh. c) graphs of dipole coregistration error on calculated sensor position and orientation error.

References

[1] R. M. Hill, et al. NeuroImage 219, 116995 (2020)
[2] C. Pfeiffer, et al. PLoS ONE 13(5): e0191111 (2018)
[3] J. Iivanainen, et al. Sensors *22*(8), 3059 (2022)

Multi-pass Magnetometer for Inherent Heading Error Reduction

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This work presents novel single beam U-shaped OPM with inherent Heading Error (HE) reduction.

Geomagnetic field magnetometers performance is affected by its orientation relative to Earth's magnetic field, mainly due to non-linear Zeeman effect which manifest as magnetic readout signal variations, i.e., heading error [1].

HE is symmetric with respect to circular polarization helicity; therefore, the common approach is to split the incoming beam into right – and left-hand polarized beams to self-compensate the HE effects [2]. In a single-beam multi-pass U-shaped implementation the incoming beam is reflected back to the vapor cell while keeping its helicity constant despite the propagation vector' reflection. This simple structure allows to achieve a cost-effective inherent HE reduction with a compact optical setup. The experimental results show more than an order of magnitude improvement in HE.

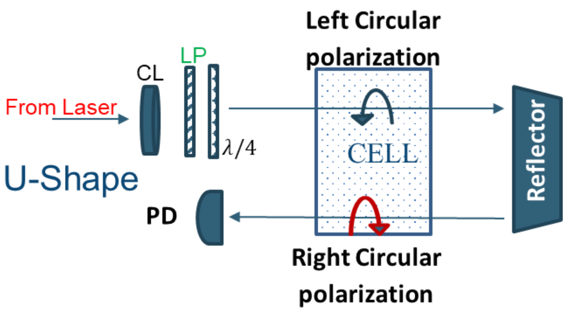

Figure 1: Sensor configuration: CL – collimating lens, LP- linear Polarizer, $\lambda/4$ – quarter waveplate, PD- photodiode.

References

[1] G. Oelsner, V. Schultze, R. IJsselsteijn, F. Wittkämper, and R. Stolz, Phy. Rev. A Phys. Rev. A **99,** 013420 (2020).

[2] T. Yabuzaki and T. Ogawa, J. Appl. Phys. **45**, 1342 (1974)..

A highly drift-stable atomic magnetometer for fundamental physics experiments

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We report the design and performance of a nonmagnetic drift stable optically pumped cesium magnetometer with a measured sensitivity of 30 fT at 200 s integration time and stability below 50 fT between 70 and 600 s. In a Bell–Bloom configuration, a higher order polarization moment (alignment) of Cs atoms is created with a pump laser beam in an anti-relaxation coated Pyrex cell under vacuum, filled with Cs vapor at room temperature. The polarization plane of light passing through the cell is modulated due the precession of the atoms. Operation is based on a sequence of optical pumping and observation of freely precessing spins at a repetition rate of 8 Hz. This free precession decay readout scheme separates optical pumping and probing and, thus, ensures a systematically highly clean measurement. Due to the residual offset of the sensor of $<$15 pT together with negligible crosstalk of adjacent sensors, this device is uniquely suitable for a variety of experiments in low-energy particle physics with extreme precision, here as a highly stable and systematically clean reference probe in search for time-reversal symmetry violating electric dipole moments. [1]

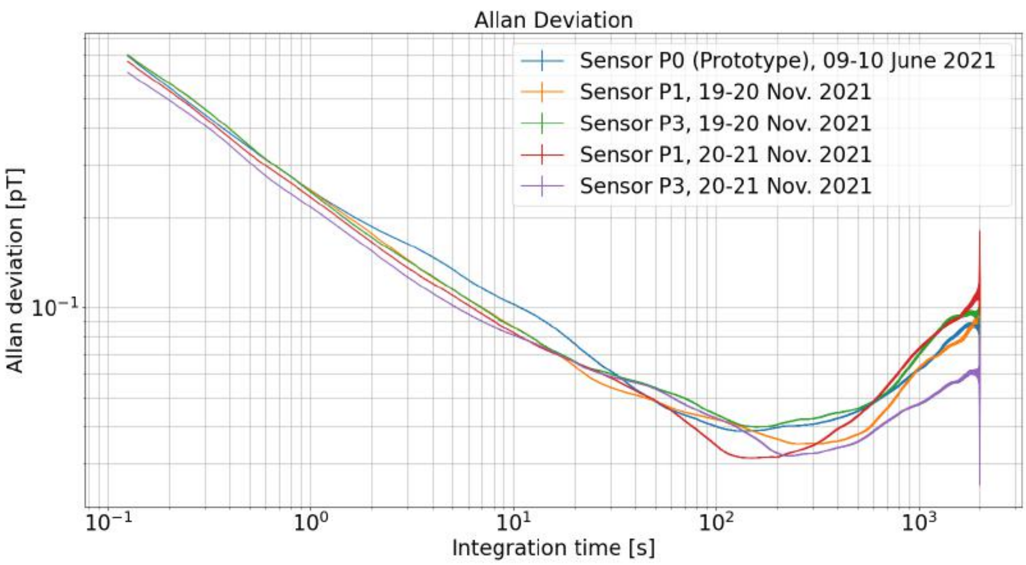

Figure 1: Allan standard deviation of measurements taken with different sensors on various days. All measurements show a stability below 50 fT between 70 and 600 s.

References

[1] M. Rosner et al, ”A highly drift-stable atomic magnetometer for fundamental physics experiments”, Appl. Phys. Lett. 120, 161102 (2022)

Eddy current measurements in unshielded conditions using a portable optically pumped magnetometer

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Electrically conductive objects can be detected, localised and characterised using the principle of electromagnetic induction. A primary oscillating magnetic field induces eddy currents in a conductive sample, which in turn produce a secondary magnetic field that can be measured with a magnetometer. This method is used in metal detectors and in industry for non-destructive testing of metallic components. The high sensitivity of optically pumped magnetometers (OPMs) makes them promising for eddy current measurements [1, 2, 3]. We here present a compact and portable OPM (Fig. 1a) based on Cesium atomic vapour which is operated in unshielded conditions. A primary magnetic field oscillating at 10 kHz corresponding to the Larmor frequency is applied. When a small aluminium sample is placed near the OPM we observe an in-phase and out-of-phase magnetometer signal (Fig. 1b). Our work is a step towards practical applications of OPMs for detection and characterisation of metal samples.

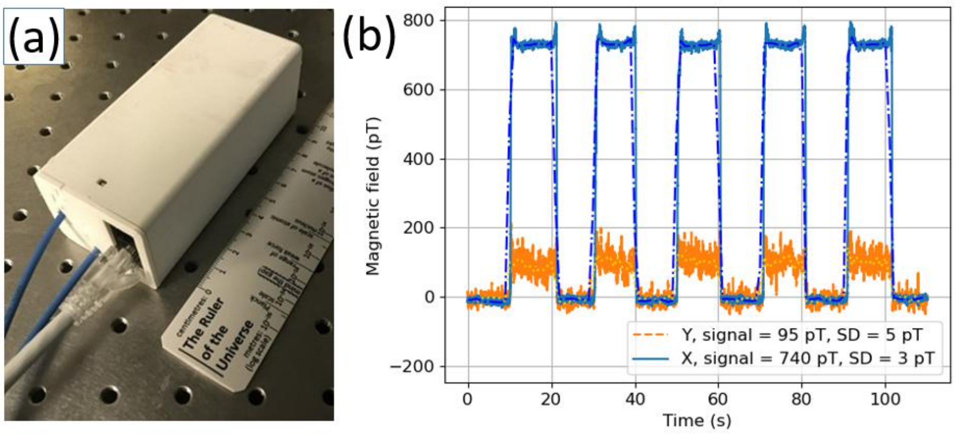

Figure 1: (a) Prototype OPM. (b) Magnetometer signal when a 3 cm aluminium disk is placed near the OPM at $t = 10$ s and then removed again at $t = 20$ s (5 repetitions).

References

[1] A. Wickenbrock, S. Jurgilas, A. Dow, L. Marmugi, and F. Renzoni. *Opt. Lett.*, 39:6367, 2014.

[2] P. Bevington, R. Gartman, and W. Chalupczak. *Journal of Applied Physics*, 125(9):094503, 2019.

[3] K. Jensen, M. Zugenmaier, J. Arnbak, H. Stærkind, M. V. Balabas, and E. S. Polzik. *Phys. Rev. Research*, 1:033087, 2019.

Atomic vapor cell-based microwave spectrum analyzer with 1GHz instantaneous analysis bandwidth

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Modern microwave spectrum analysis requires a wide instantaneous analysis bandwidth, particularly when assessing signals of unknown frequencies [1,2]. The traditional fast Fourier transform (FFT) method typically provides up to a few GHz analysis bandwidth, which is limited by the performance of the analog-digital converter (ADC). We demonstrate an atomic microwave spectrum analyzer with a ~1GHz instantaneous bandwidth using MEMS Rb vapor cells. A static magnetic field gradient across the cell results in a position-dependent atomic hyperfine transition frequency, mapping the frequency of an applied microwave to the position of the atomic response in the cell. A moderate amount of Nitrogen buffer gas [3] ensures that only a narrow region of Rb atoms responds to a given microwave frequency.

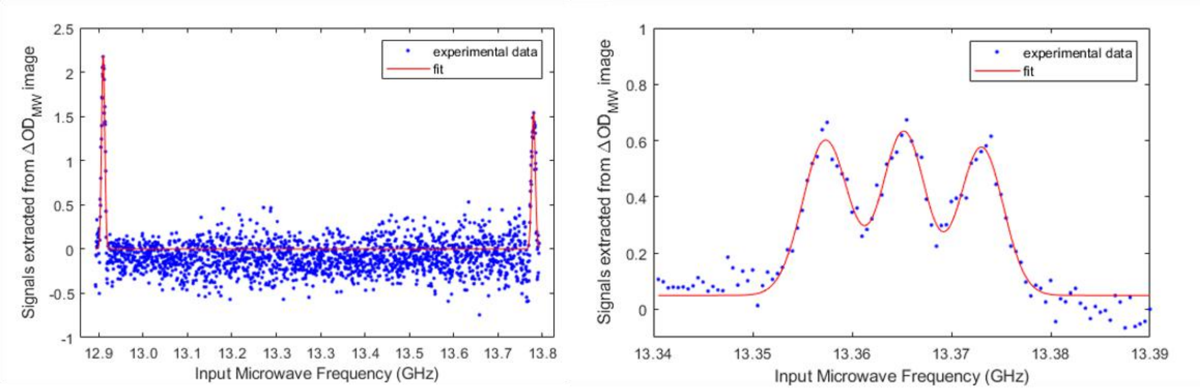

Figure 1: (Left) The measured instantaneous bandwidth is ~1GHz;
(Right) The frequency resolution bandwidth is ~8MHz.

We extract the frequency spectrum of microwave signals on a coplanar waveguide from absorption images of the induced change in optical density of the vapor. The frequency resolution is approximately 8MHz, consistent with the prediction based on atomic diffusion in the magnetic field gradient. We develop a theoretical model for the signal and propose an optimized design to increase sensitivity and bandwidth.

References

[1] V. Teppati, F. Andrea, and S. Mohamed, eds. Modern RF and microwave measurement techniques. Cambridge University Press (2013).

[2] M. Chipaux, L. Toraille, C. Larat, L. Morvan, S. Pezzagna, J. Meijer, and T. Debuisschert, Applied Physics Letters 107, 233502 (2015).

[3] A. Horsley, and P. Treutlein. Applied Physics Letters 108, 211102 (2016).

Toward an Optically Pumped Magnetometer Magnetoencephalography System with Full Head Coverage

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[3]*Candoo Systems,* [4]*Mind Research Network*
[5]*Institute for Learning and Brain Sciences, University of Washington*

We will present various aspects of our development effort to implement a 108-channel optically pumped magnetometer (OPM) array in a magnetically shielded room (MSR). Our four-channel OPM [1] has been redesigned to ease manufacturing, reduce the external temperature, improve the magnetic field control and uniformity, and reduce the required optical power, while maintaining or improving the sensitivity (see Figure 1) and bandwidth. With laser light delivered to our OPM modules via optical fiber, we have designed and are starting to implement a light distribution system for our two-color pump/probe OPM. Finally, we will outline efforts to develop custom control hardware and software, OPM array calibration approaches, and an MSR with magnetic field control.

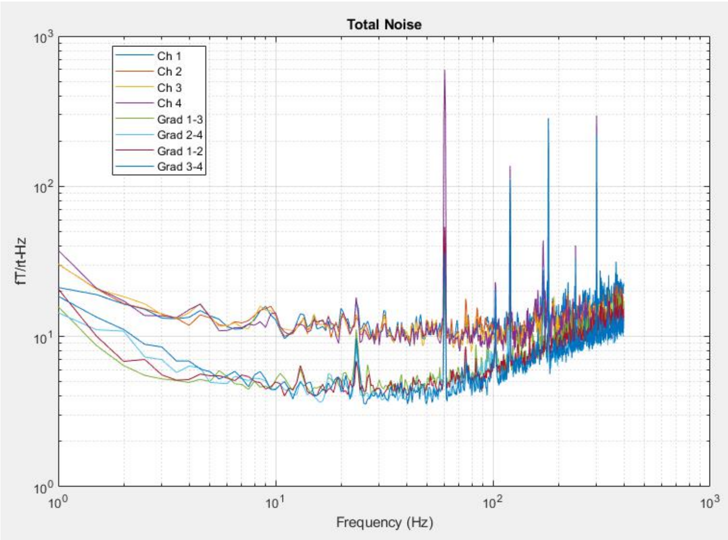

Figure 1: Magnetic sensitivity and gradiometric-inferred sensitivity of the four channels of the OPM module.

References

[1] A. P. Colombo, Optics Express **24**, 15403-15416 (2016).

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Hybrid Scalar-Triaxial Atomic Magnetometer

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Non-zero field atomic magnetometers measure the scalar value of the magnetic field, $|\vec{B}|$. Here we describe our progress in developing a hybrid scalar + triaxial atomic magnetometer based on free-induction decay. In analogy with a pseudo-scalar magnetometer made by combining the outputs of three orthogonal vector (fluxgate) magnetometers, we build a pseudo-triaxial vector magnetometer from a scalar magnetometer by applying external bias fields (<3 pT/√Hz scalar and <15 pT/√Hz vector). We find the low-frequency stability and accuracy of a pseudo-vector magnetometer can significantly exceed current state-of-the-art vector magnetometers. We will discuss the benefits of a hybrid scalar-triaxial atomic magnetometer for magnetic anomaly detection (MAD) and other geophysical applications.

In addition, we will also describe our progress in developing a compact, zero-field triaxial vector magnetometer. Triaxial sensitivity is obtained by splitting the input laser beam into two halves, with each half forming an independent magnetometer using the same vapor cell [1]. The technique enables triaxial operation without increasing the size, weight, or power consumption of the sensor head and without significant reduction in its sensitivity. We will briefly discuss the significant impact of triaxial sensors on the architecture of on-scalp MEG systems.

References

[1] Boto E., NeuroImage, 119027, 2022

Mass-producible miniature atomic-vapor sensors

L. Balet[1], S. Bodenstedt[2], J. Haesler[1], D. Hunter[3], S. Karlen[1], M. Lahti[4], P. Laine[5], V. G. Lucivero[2], M. W. Mitchell[2,6], K. Mouloudakis[2], T. Overstolz[1], L. Parkkonen[5,7], C. Pfeiffer[8], H. Sipola[4], M. C. D. Tayler[2], C. Troullinou[2], J. White[5], R. Zetter[5,7]

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Recent years have seen several atomic-vapor device prototypes (e.g. atomic clocks, magnetometers) enter the commercial market thanks to miniaturized package designs [1] and cost-effective methods for manufacture on the 100-1000 unit scale. In this presentation, we report further progress towards large-scale production [2]. We demonstrate: femtotesla magnetometry using high-buffer-gas-pressure, mm-scale atomic vapor cells fabricated via MEMS techniques [3]; biplanar printed-circuit coils for highly homogeneous and localized magnetic field control [4]; package integration. We also discuss methods to enhance the performance of microfabricated atomic devices including resonant optical cavities and spin squeezing techniques.

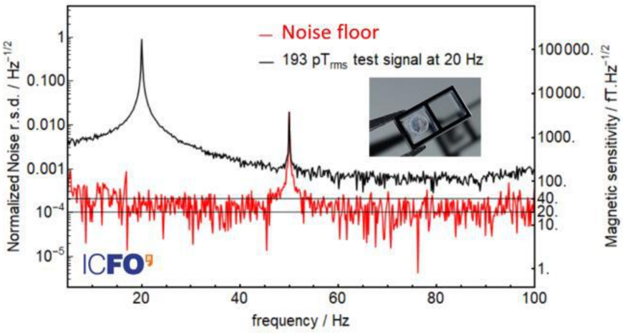

Figure 1: Magnetic noise measurement using a MEMS ^{87}Rb vapor cell and miniature biplanar coils – two components of a mass-manufacturable atomic magnetometer.

References

[1] S. Knappe, *Comprehensive Microsystems* vol. 3, pp. 571-612, Elsevier (2007).
[2] https://www.macqsimal.eu
[3] S. Karlen, J. Gobet, T. Overstolz, J. Haesler, and S. Lecomte, *Optics Express* vol. 25, 2187-2194, (2017).
[4] M.C.D. Tayler et al., preprint *arXiv:2204.01370*, (2022).

A modular system for optically pumped magnetometry

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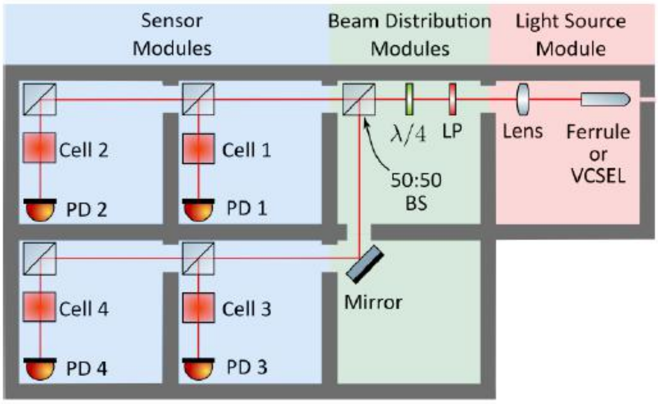
We present a modular optically pumped magnetometer (OPM) system that allows for rapid prototyping and testing of measurement schemes for a variety of medical [1] and industrial [2] applications. The system comprises self-contained modules – made of 3D-printed polycarbonate – containing either sensors, beam distribution components, or light sources, allowing for quick and simple reconfiguration of the overall geometry of the device [3].

The modularity of the design allows for scaling to an array of modules, all with a common light source, and provides a testbed for the development of techniques for controlling high-density arrays for both medical and industrial sensing applications. As an example of one type of application, we report measurements of alpha-rhythm activity in the brain of a human participant, obtained from a modular OPM array.



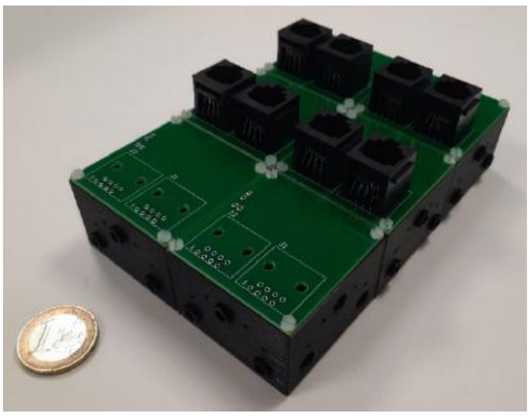


Figure 1: A schematic (left) [3] and photograph (right) of the modular OPM system, with a coin for scale. Modules can be easily snapped together to produce different configurations for various applications.

References

[1] 'Improved spatio-temporal measurements of visually evoked fields using optically pumped magnetometers', A. Gialopsou et al., *Sci. Rep.* **11**, 22412 (2021).

[2] 'Non-invasive current density imaging of lithium-ion batteries', M. G. Bason et al., *J. Power Sources,* Vol. 533, 231312 (2022).

[3] 'Modular optically pumped magnetometer system', T. Coussens et al., *arXiv:2106.05877* (2021).

A study of alpha rhythm and sensorimotor cortex responses using optically-pumped magnetometers (OPMs)

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The proportional-integral-derivative controller-based dynamic nulling system was constructed to adapt to the working environment of OPMs in our previous work. Measurement was acquired under different environmental conditions to test the system's capacity for neuromagnetic signal detection. Multiple experimental paradigms involving alpha rhythm and sensorimotor cortex response were designed.

We measured the photic blocking of alpha rhythm in the occipital lobe when the subject switches between eyes-open and eyes-closed states. The sensorimotor cortex responses following electrical stimulation of the median nerve and voluntary movements of the index finger were measured, respectively. The signal-to-noise ratio (SNR) of the MEG signal was calculated and compared under four different conditions: noisy magnetic field environment (daytime with the impact of underground, field drift >±20nT) with the dynamic nulling system on, clean environment (late night with field drift<±1nT), clean environment with only static field nulling, clean environment with dynamic nulling. Additionally, a preliminary source localization analysis was performed.

Clear alpha rhythm, good time-course, and magnetic field topographic maps of somatosensory evoked fields (SEFs) and movement-related cortical fields (MRCFs) were obtained. Theta band oscillation during movement execution and the post-movement beta rebound was also observed. The above results are consistent with the signal collected by SQUID-MEG. It shows that our system has the capacity for neuromagnetic signal detection. The highest SNR was achieved under a good environment with dynamic nulling, which suggests that even in a good magnetic field environment with slight background drift, an adaptation using a dynamic nulling system can still improve the SNR of the acquired neural signal. We will further evaluate its impact on source localization accuracy in future works.

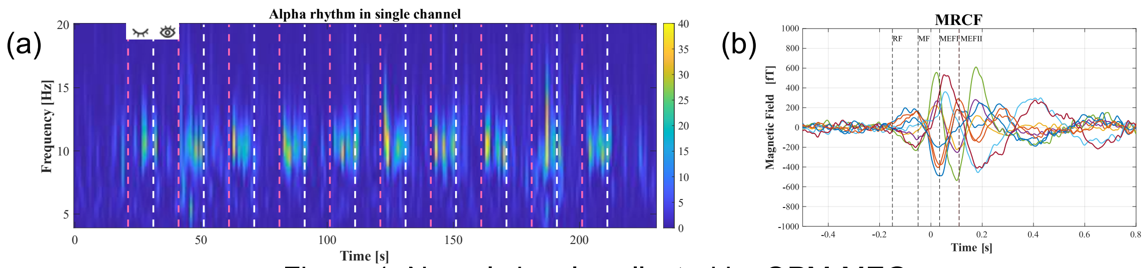

Figure 1. Neural signals collected by OPM-MEG.
(a) Spectrogram of the alpha rhythm. (b)Time-course of MRCFs.

Effects of head model errors on the spatial frequency representation of MEG

W.-J. Yeo[1,2], E. Larson[2], J. Iivanainen[3], A. Borna[3], J. McKay[4], J. Stephen[5], P. D. D. Schwindt[3], and S. Taulu[1,2]

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It can be shown that return currents are mathematically equivalent to surface current distributions on the head model surfaces [1], and hence accurate head models are important in accurately calculating their signal contributions. We show that by reducing the sensor-scalp gap, inaccurate boundary-element calculations of the head model result in higher magnetoencephalography signal and source localization errors in the noiseless case. This is due to higher spatial frequency components having higher errors (Figure 1). However, in the noisy case beyond a signal-to-noise-ratio (SNR) of ~6 dB, higher SNRs for reduced sensor array distances allow for more accurate source localizations; the negative effects of high frequency components having higher errors are outweighed. Thus, for optically-pumped magnetometer sensor arrays that can be placed closer to the head with higher SNR, accurate head models become increasingly important.

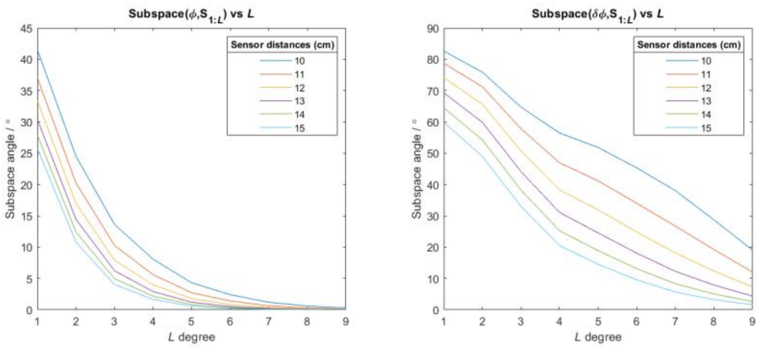

Figure 1: (Right) Signal errors $\delta\boldsymbol{\Phi}$ have higher subspace angles with vector spherical harmonic basis truncated at the L^{th}-degree ($\mathbf{S}_{1:L}$), and requires higher L truncation to explain when compared to the true signal $\boldsymbol{\Phi}$ case (left). This means $\delta\boldsymbol{\Phi}$ contain higher-frequency components with higher errors than $\boldsymbol{\Phi}$.

References

[1] D. Geselowitz, "On the magnetic field generated outside an inhomogeneous volume conductor by internal current sources," in *IEEE Trans. Magn.*, **6**(2), 346-347 (1970).

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OPM-MEG from a commercial perspective – opportunities and challenges

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As the leading manufacturer of magnetoencephalography (MEG) technology, MEGIN OY is committed to staying abreast of advancements of technologies that could be used in our commercial devices. Optically-pumped magnetometers (OPMs) are currently receiving substantial attention by researchers and commercial operators alike, for which reason we believe that it is timely to share some of our strategic thinking and actions related to this technology. We discuss some of MEGIN's OPM-related activities, including but not limited to collaboration and in-house development. Further, we showcase specific advantages and disadvantages of different OPM technologies as they relate to commercial MEG devices. Finally, we present a list of technical challenges that are still left to be solved for OPMs to be acceptable for clinical use in a medical device.

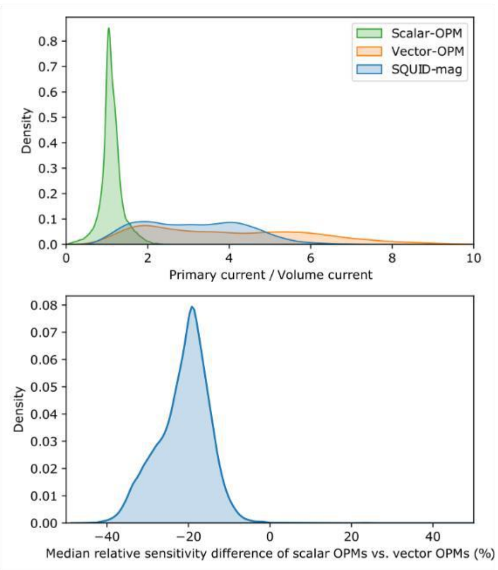

Figure 1: Top left: Ratio between primary and volume current contribution to measurements by scalar and scalp-normal-vector MEG systems. Bottom left: Relative sensitivity of scalar and scalp-normal-vector OPM measurements, across all background field directions. Right: Coil system for cancelling all homogenous and 1st-order gradient-field components, especially useful when operating in challenging magnetic environments.

A preliminary study of magnetic field noise suppression method towards the moving magnetoencephalography

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In a commercially available magnetic shielding room, the low frequency magnetic field drift could easily make the zero-field optically pumped magnetometer (OPM) go out of its dynamic range. Here, a dynamic nulling system was constructed inside the shielding room, it consists of proportional-integral-derivative (PID) controllers, bi-planar coil system produced by Nottingham-MSL and OPMs from QuSpin Inc. The magnetic field was successfully stabilized within ±1nT in the interested region with our system.

However, the system also induces noise for OPM-MEG system. Hence we evaluated this noise characteristic in different magnetic field environments. In order to reduce this noise impact through data analysis, synthetic gradiometry and homogeneous field correction (HFC) were applied and compared. To test this system's capacity of noise suppression in signals detection, a series of phantom-based study was performed. In the experiment, a sinusoidal-type magnetic field was produced by a magnetic dipole phantom, and the signal to noise ratio was measured and compared between different field environment.

The results show that induced noise could be greatly suppressed, through real-time smoothing the PID system output and increasing the feedback system's response speed. Besides, HFC method could reject both the induced noise and other common-mode noise better. The source localization result fits the location of dipole in the phantom well. However, there is still some problem such as the HFC method still leads to a reduction in signal strength and its performance is related to the distribution of the sensors' orientations. Further improvement of the PID and noise reduction method is important for OPM-MEG.

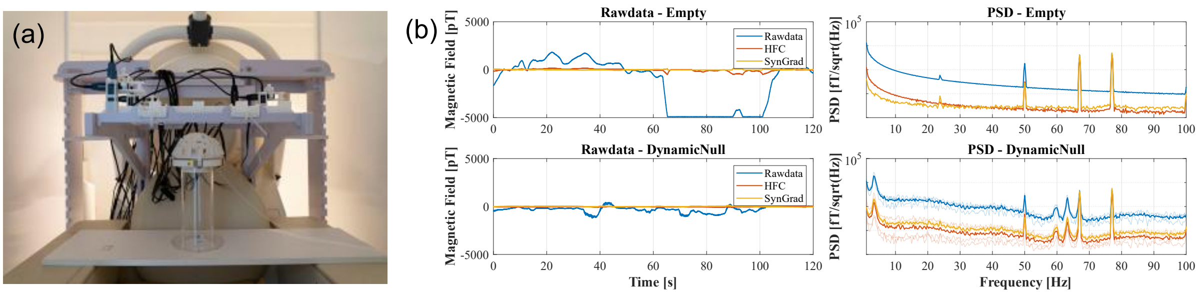

Figure 1: (a) Phantom experiment setup. (b) Comparison results of different field environments.