Workshop on optically-pumped magnetometers - WOPM2025

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Book of Abstracts

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Industrial Application of OPM: Flow Metering

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We present a noninvasive flow metering technique that employs optically pumped magnetometers (OPMs) for measuring fluid flow velocities through a novel magnetic-marking approach. The method utilizes polarized hydrogen nuclei within the fluid, which are polarized with a permanent magnet. Radio frequency (RF) pulses are applied to the fluid to create local magnetic marks in the otherwise magnetized fluid. These marks serve as time stamps to enable a time-of-flight measurement, facilitating accurate flow velocity determination without the use of tracers. The OPMs, operating in nano Tesla residual fields, can detect induced magnetic signals as low as 10 pT or less.

A primary focus of this work is the impact of flow profiles on the magnetization distribution within the fluid. Our work focuses on how the radial distribution of flow velocities influences the effectiveness of RF pulsing and the resultant magnetic signals. We have simulated the magnetization distribution in a flowing medium, revealing that varying flow velocities lead to different retention times in the RF field, which in turn affects the magnetization state and the magnetic signal detected by the OPM. The findings demonstrate that the flow profile significantly impacts the quality and characteristics of the magnetic mark in the fluid, paving the way for optimizing flow metering systems based on OPM technology. This work highlights the significant potential of OPMs in advancing an industrial application case such as noninvasive flow measurement techniques.

OPM Development I / 6

Magnetic resonance linewidth of alkali-metal atoms and systematic error of comagnetometer

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The investigation of magnetic-resonance linewidth is of fundamental importance in the field of magnetic-resonance physics and its diverse applications. Previous research has predominantly focused on the linewidth of alkali metal atoms within two distinct regimes: the spin-exchange relaxation-free (SERF) regime near zero magnetic field, and strong magnetic fields where Zeeman resonances are clearly resolved due to the quadratic Zeeman effect. However, the linewidth behavior in the unresolved-Zeeman-resonance (UZR) regime, which is commonly encountered in various magnetometer and comagnetometer applications, remains unclear.

By solving the master equation for alkali metal atoms under the rotating-wave approximation and weak-driving conditions, we reveal that the linewidth in the UZR regime is significantly influenced by the mutual coupling of quantum coherence between different Zeeman sublevels[1]. Leveraging this understanding of the linewidth, we present our recent findings on the systematic error in comagnetometers induced by small changes in the Rb resonance linewidth[2,3]. These results are expected to be highly beneficial in enhancing the long-term stability of comagnetometers.

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Poster Session and Buffet / 7

Towards an optically pumped spin-precession, magnetometric camera

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We have developed a magnetic field camera for detecting defects in metal components and battery imaging.

Our approach leverages the high sensitivity and robustness of free-spin-precession (FSP) and Mz magnetometry, combined with a fast, commercial camera operating at up to 90kHz.

Unlike current state-of-the-art optically pumped magnetometers (OPM), which record single or few data points using custom-made diode arrays, we image the entire volume of the rubidium cell directly onto the camera.

This method allows us to read out spatially resolved magnetic field strengths with $200 \mu m$ resolution in parallel, enabling time-efficient data acquisition at an experimental validated sensitivity of $100 pT$.

OPM Applications II / 8

Fundamental issues on applications of atomic magnetometry

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In this talk, I will give an overall introduction on our recent progresses on the applications of high sensitivity atomic magnetometry in this field of biomagnetism, magnetic-field standard, and searches for exotics physics. For biomagnetism, I will introduce the basic idea of measuring the bio-magnetic field signals with atomic magnetometers in unshielded environment, as well as the significance and potential applications of measuring magnetic field signals from different organs of the human being. For magnetic-field standard, I will introduce our recent work on the active magnetic field stabilization with atomic magnetometers, including the basic principle of generating a magnetic field with both high precision and low noise level. For probing the frontiers of the fundamental physics, I will introduce several kinds of novel design and adaptation of the atomic magnetometry, all of which are focused on suppressing the different kinds of systematic errors in the searches for exotic physics beyond the standard model.

Poster Session and Buffet / 9

Frequency Shift Caused by Nonuniform Field and Boundary Relaxation in Magnetic Resonance and Comagnetometers

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In magnetic resonance experiments, it is widely recognized that a nonuniform magnetic field can lead to an increase in the resonance line width, as well as a reduction in sensitivity and spectral resolution. However, a nonuniform magnetic field can also cause shifts in resonance frequency, which has received far less attention. In this work, we investigate the frequency shift caused by boundary relaxation and nonuniform magnetic field with arbitrary spatial distribution. We find that this frequency shift is spin-species dependent, implying a systematic error in NMR gyroscope and comagnetometers. The first order correction to this systematic error is proportional to the difference of boundary relaxation rate, and dominates for small cells. In contrast, the third and higher order corrections arise from the difference of gyromagnetic ratios of spin species, and dominates for large cells. This insight helps understanding the unexplained isotope shifts in recent NMR gyroscope and new physics searching experiments that utilize comagnetometers. Finally, we propose a tool for wall interaction research based on the frequency shift's dependency on boundary relaxation.

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Laser sealing for atomic devices

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Microfabricated alkali vapor cells are central to the development of compact and low-power atomic devices such as atomic clocks and optically pumped magnetometers (OPMs). However, conventional microfabrication techniques, particularly those relying on anodic bonding for final sealing, impose high temperatures that are incompatible with the integration of antirelaxation coatings.
In this work, we present a novel filling and sealing method for microfabricated vapor cells that leverages locally-sealed microchannels etched into the glass substrates. The heat induced by the sealing is local, and paves the way for post-fabrication deposition of temperature-sensitive antirelaxation coatings such as paraffin. It opens the perspective of significantly reducing the operating temperature of OPMs, a key factor in eliminating the need for thermal isolation, thereby allowing closer proximity to the signal source and facilitating integration into wearable and portable platforms.

Poster Session and Buffet / 11

Microfabricated Alkali Metal Vapor Cells Based on Ultrafast Laser Welding

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The miniaturization of optical pumping magnetometer became the focus of research, and the miniaturization of the alkali metal vapor cell is the key to the miniaturization of the atomic magnetometer. The development of micro-electromechanical systems (MEMS) provides the basis for miniaturization of alkali metal vapor cells. The sealing of MEMS vapor cells was mainly realized by anodic bonding, however, the high bonding temperature as well as the high-voltage in the anodic bonding process would adversely affect the fabrication of MEMS vapor cells. In this study, a method for the fabrication of MEMS alkali metal vapor cell based on ultrafast laser welding was proposed. The fabrication of the silicon cavities was realized by dry etching and chemical polishing, following which the bonding of the silicon and glass plates was realized by ultrafast laser welding. After that, the injection of alkali metal and the buffer gas were accomplished in the constructed welding system, and finally the sealing of the MEMS vapor cell was also achieved by ultrafast laser welding. The vapor cell was heated under vacuum at 150 ℃ for 15 days and the absorption spectra were tested. The results showed that the leakage rate of the vapor cell with He was about 7.4 × 10-10 Pa·m3/s, which was comparable to the anodic bonding leakage rate. In addition, the small heat affected zone of ultrafast laser welding provides a new approach for the fabrication of integrated anti-relaxation coated MEMS vapor cells, which is the focus for our further work.

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A chip-scale SERF atomic magnetometer based on micro-fabricated bi-planar coil

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In mobile magnetoencephalography (MEG) systems, hundreds of atomic magnetometer sensor heads are typically deployed, making the miniaturization of atomic magnetometers essential. The coils used for spin modulation and magnetic-field control are critical components of these devices. Here, using microelectromechanical systems (MEMS) technology, we have designed and fabricated a three-dimensional bi-planar coil with compact dimensions of 9 mm × 8 mm, as well as a heating coil measuring 9 mm × 6 mm. By combining femtosecond laser welding with MEMS processes, we also produced an alkali-metal vapor cell of only 6 mm × 4 mm × 3 mm. Building on the miniaturization of these components, we developed an integrated, micro single-beam spin-exchange relaxation-free (SERF) atomic magnetometer. This device combines the microfabricated bi-planar coil, the microfabricated heater chip, and the microfabricated alkali-metal vapor cell, and incorporates both a pump and a probe optical path. The probe housing, fabricated by laser sintering of glass-fiber material—measures just 43 mm × 12 mm × 15 mm, achieving an internationally leading level of integration among comparable magnetometers.

Poster Session and Buffet / 13

Zero-field optically pumped magnetometer with thin vapor cell and 16 channels

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We present a zero-field optically pumped magnetometer that utilizes a thin microfabricated vapor cell, offering 16 measurement channels within the same cell. The vapor cell and its thermal insulation have been optimized to minimize the distance between the magnetic sample and the sensing volume, thereby enhancing the effective spatial resolution. Initial measurements indicate that all channels achieve a photon-shot-noise limited noise floor in the $\frac{pT}{\sqrt{\mathrm{Hz}}}$ range for a sensitive voxel size of approximately 600 µm x 600 µm x 200 µm. The best channel reached 1.4 $\frac{pT}{\sqrt{\mathrm{Hz}}}$ noise floor.

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In-situ residual magnetic compensation for zero-field NMOR atomic magnetometer

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Recent decades have witnessed considerable interest in nonlinear magneto-optical rotation (NMOR) atomic magnetometer, which has demonstrated high sensitivity and low error in both near-zero field and geomagnetic environments [1,2]. However, the presence of residual magnetic field in magnetically shielded devices often damages the performance of zero-field NMOR atomic magnetometer [1].
In this study, considering the presence of the residual magnetic field, we develop the response model of zero-field NMOR atomic magnetometer and analyze the effect of triaxial residual magnetic fields on magnetometer. Then a triaxial in-situ residual magnetic field compensation method based on sinusoidal magnetic field modulation is proposed, which is shown as Fig. 1(a). The sensitivity of magnetic field measurement after residual magnetic field compensation is 19 $\mathrm{fT/Hz^{1/2}}$, reflecting a 56% improvement over the uncompensated case. In addition, the noise affecting the sensitivity of the magnetometer is evaluated, shown as Fig. 1(b). The sensitivity after residual magnetic compensation is close to the detecting background noise, which is 14 $\mathrm{fT/Hz^{1/2}}$. This method is of significance for the construction of zero magnetic environment and detection of weak magnetic field in human body.

Figure 1: (a) Residual magnetic compensation method based on sinusoidal magnetic field modulation (b) Sensitivity and noise assessment

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Quantum and Fundamental / 15

Magnetic Field Optimisation and Design Procedures for Quantum Sensing Applications

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High-precision control of magnetic fields is critical for the operation of a range of quantum technologies. For example, optically pumped magnetometers (OPMs) utilise electromagnetic conductor networks within sensor housings to generate zero-field environments and modulation or bias fields. Current-carrying systems are also used within magnetically shielded rooms for hybrid active-passive magnetic field shaping and system calibration for OPM-based magnetoencephalography systems.

For any conductor network, topological optimisation ensures that currents produce high-fidelity magnetic fields with specified shape and strength. We have developed several optimisation methodologies including discrete and distributed current approaches, which incorporate apriori the effects of high-permeability materials on the field profiles. We have also developed methods for converting optimised conductor network designs to functioning hardware, including Printed Circuit Board (PCB) track milling/printing, wire winding on 3D printed formers for low power dissipation, and a full PCB design pipeline. The latter encompasses connection between conducting tracks, locations of vias and connection pads, track width and depth, and testing to ensure that the finalised PCB generates the desired field accurately and within size, weight and power constraints. We have also developed methods for optimising the layout of permanent magnets in cases where the field is continually required.

Here, we will present the implementation of our PCB design pipeline and optimisation methods, highlighting the improvements that resulted from a range of different projects and magnetic field requirements, and through interactions with project partners and industry contractors. These projects include designing and miniaturising bias coil flex PCBs for an RF magnetometer, shimming and nulling coils for use within a shielded CubeSat, and advances on permanent magnet optimisation for applications such as quantum computing.

Poster Session and Buffet / 16

Polarization dynamics of triaxial modulation SERF atomic magnetometers

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Triaxial spin-exchange relaxation-free (SERF) atomic magnetometers (AMs) provide more comprehensive magnetic field information in bio-magnetic measurements, effectively improving the accuracy of magnetic source reconstruction. Typically, the triaxial AM is considered to be three independent orthogonal single-axis AMs, but the interaction of the triaxial modulation is ignored. This study established polarization dynamics under triaxial modulation, providing a theoretical model for triaxial AMs. Based on the perturbation iteration theory, the modulation field along the cross-axis is regarded as a perturbation term. Subsequently, the polarization dynamics model is established by summing the steady-state and multiorder perturbations of the triaxial polarization projections. Based on the proposed model, we discovered an optimal modulation coefficient formula for the triaxial SERF AM, replacing the constant optimal coefficient used when treating it as three independent single-axis AMs. The proposed optimal modulation coefficient exhibited a 12% improvement in response relative to the conventional coefficient. The proposed polarization dynamic model is beneficial for further investigation of triaxial SERF AMs and contributes to the improvement of their sensitivity.

Poster Session and Buffet / 17

Single-Beam Vector Atomic Magnetometer for Wide-Range Magnetic Field Measurements with Simultaneous Triaxial Modulation

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In practical applications such as earthquake early warning, environmental magnetic field compensation, and geomagnetic navigation, magnetic sensors are typically required to measure both the magnitude and direction of the magnetic field[1]. Consequently, high-sensitivity vector atomic magnetometers have become an important research focus[2]. Although various schemes have been developed, limitations in sensitivity, dynamic range, and system complexity continue to restrict their practical deployment.
In this work, we present a high dynamic range vector atomic magnetometer based on nonlinear magneto-optical rotation (NMOR) with triaxial magnetic field modulation. A phase-locked loop (PLL) tracks the resonance frequency of atomic multipole moments to measure the magnetic field magnitude, while directional information is extracted through secondary demodulation of optical rotation signals under three-axis magnetic filed modulation. Our magnetometer achieves a modulus sensitivity of 500 fT/Hz$^{1/2}$, a polar angle sensitivity of 0.29 mrad/Hz$^{1/2}$, and an azimuthal angle sensitivity of 0.94 mrad/Hz$^{1/2}$, enabling real-time measurement of dynamically varying vector magnetic fields.

Figure 1: Measurement results of the vector NMOR atomic magnetometer.

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Poster Session and Buffet / 18

Improving Magnetic Field Unformities for Quantum Sensing with Advanced PCB Design

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Strict magnetic field control is an integral part of quantum sensors such as optically pumped magnetometers (OPMs). OPMs are used in pioneering research including biomagnetic measurement, which utilises hybrid shielding to provide the low and stable field environment required for precise measurements. Further applications where controlled field environments are required include atom interferometry for inertial navigation, graviometry, or other fundamental physics measurements. Controlled fields are also needed for the design, development and testing of OPMs themselves.

In hybrid systems, electromagnetic coils must be optimised to produce a desired field within the system geometry and accounting for the response of high permeability alloys, such as mu metal. Due to the complexity, each use case will require a different coil design for peak performance. The current standard for cylindrical geometries incorporates one Flexible Printed Circuit Board (or Flex-PCB) for each desired field, with the coil traces printed onto the PCB. This approach, which reliably sees uniform fields produced with <0.5% deviation in the fields along the target region, is effective, but alternative coil design methodologies can also be explored.
Here, we present coil design methodology and manufacturing advancements including multi-face coils. This involves simultaneously optimising multiple coils together to produce a single, more uniform, field. The field fidelity can also be further improved through multi-surface coil design that builds on the standard cylindrical or planar coil by including endcaps further enclosing the geometry. We also present multi-layer coils, that take advantage of advanced PCB manufacturing techniques to combine standard coil designs into a single, multilayer, Flex-PC. This approach mitigates alignment errors found with multiple single-layer Flex-PCBs, thereby improving field fidelity.

Poster Session and Buffet / 19

SERF Comagnetometer Based on Self-differential Mode

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Spin-exchange relaxation-free (SERF) comagnetometer is significant in exploring fundamental physics and high-precision inertial sensing. However, traditional continuous measurement based on steady atomic spin polarization limits the suppression of long-term drifts, which is pivotal for inertial navigation and the search for new physics beyond standard model.We propose a SERF comagnetometer based on self-differential measurement mode using reverse-modulated atomic spin polarization for signal enhancement and noise suppression, as is shown in Fig.1(a). We analyze the dynamic evolutions of alkali electron spin and noble-gas nuclear spin under the pulsed left- and right-circularly polarized pumping scheme. To ensure that the comagnetometer operates in self-compensation regime[Phys. Rev. Lett. 130 . 063201(2023)], we reverse the electron spin while keeping the nuclear spin polarization stable by optimizing the modulation period and duty cycle. Through self-differential, the response of the comagnetometer is improved by 2.95 dB and the low-frequency common-mode at 0.1˜2 Hz is suppressed by about 6.53 dB. As is shown in Fig.1(b), the sensitivity is improved by 2.7 times to $3.1 \times 10^{-6}\,^{\circ}/\mathrm{s}/\sqrt{\mathrm{Hz}}$ @1 Hz compared with the traditional continuous measurement mode.

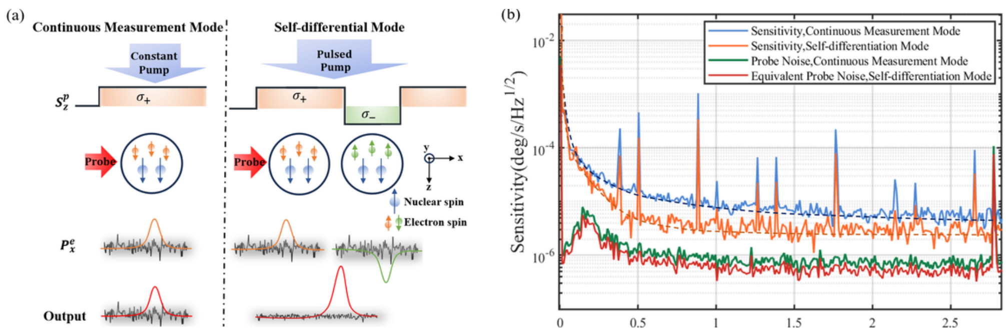

Figure 1: (a) Principle (b) Sensitivity and probe noise of SERF comagnetometer based on continuous measurement mode and self-differential mode.

Poster Session and Buffet / 20

Ultrasensitive comagnetometer with cooperative coherence transfer

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Comagnetometers have enabled significant progress in searches for physics beyond the standard model and inertial navigation, owing to the ability to substantially suppress magnetic noise. We present a novel type of comagnetometer based on the **cooperative coherence transfer** (CCT) mechanism [Submitted]. The **nonreciprocal coupling** is introduced to enable optimized **transfer energy matching** and improve the **transfer efficiency**. We demonstrate this mechanism in a ^{21}Ne-Rb-K comagnetometer, yielding a **15-fold** enhancement of the magnetic noise suppression effect compared to the conventional self-compensation (SC) regime [Phys. Rev. Lett. 89. 253002 (2002)]. Consequently, an ultrahigh sensitivity of $7.7 \times 10^{-7}\ ^\circ/\mathrm{s}/\sqrt{\mathrm{Hz}}$ from 0.2 to 1.0 Hz, equivalent to 8.7×10^{-24} $\mathbf{eV}/\sqrt{\mathbf{Hz}}$, is achieved, demonstrating **the highest energy resolution** [Quantum Sci. Technol. 7. 014001 (2022)]. This platform facilitates potential improvements of **over 4 orders of magnitude** in constraints on dipole-dipole interaction and monopole-dipole interaction, with broad application prospects.

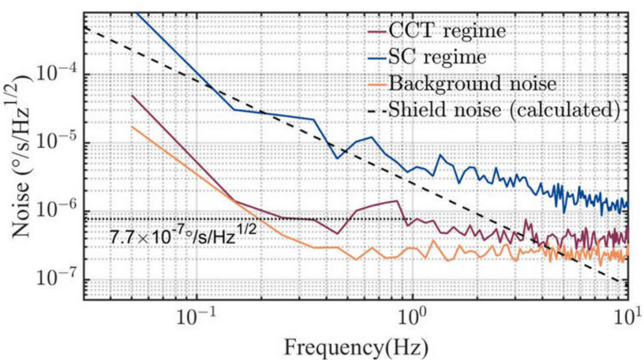

Figure 2: Noise spectrum of the comagnetometer. The background noise is obtained from the noise spectrum of unpolarized atoms. The shield noise, arising from the ferrite magnetic noise, is calculated based on the measured data.

Poster Session and Buffet / 21

Enhancing Faraday Rotation Effect in SERF Co-Magnetometers Using Multi-Reflection Cavities

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Enhancing the interaction strength between light and atoms amplifies the Faraday rotation effect, thereby improving the measurement sensitivity of optical rotation detection. This work integrates a multi-reflection cavity into the vapor cell of the SERF co-magnetometer for the first time, increasing the interaction strength between light and atoms. We establish a model that accounts for light propagation in multiple directions, clarifying the impact of the sensitive-axis component on the output signal and improving the system's measurement accuracy. Subsequently, we propose a method for calculating the number of reflections within the cavity based on light absorption, which ensures the stable and effective operation of the multi-reflection cavity in the SERF co-magnetometer. Experimental results show that the Faraday rotation effect is enhanced by a factor of 13.6 compared to single-pass, which closely matches the designed 14 reflections, thereby verifying the accuracy of the response model and the reflection count measurement. This study provides a pathway toward improving the sensitivity of SERF co-magnetometers and supports further exploration of applications in fundamental physics.[Phys. Rev. Lett. 130 . 063201(2023),Commun. Phys. 7. 226(2024)]

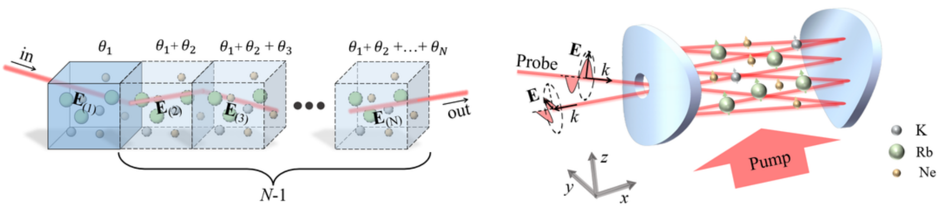

Figure 3: Schematic of enhance interaction of light with atoms.By increasing the number of media N-1 to enhance the interaction strength of light with atoms.

OPM Development III / 23

Implementation of an atomic free spin precession magnetometer targeted at medical diagnostics

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We report on the progress of implementing an atomic magnetometer based on free spin precession using our in-house manufactured rubidium-87 MEMS (micro-electromechanical systems) vapor cells. The magnetometer employs a pulsed pump and probe laser scheme, featuring a double pass through the vapor cell configuration for the probe laser beam. The magnetometer currently exhibits a sensitivity of 300 $\mathrm{fT/Hz^{1/2}}$ with a bandwidth of 500 Hz. The high dynamic range of the device, which ranges up to magnetic field strengths in the Earth's field regime, allows for a wide range of applications, e.g. the detection of biomagnetic signals from the human body, specifically signals stemming from cardiac activity. Finally, we will discuss the potential for a compact design in future iterations.

OPM Applications II / 24

Towards Optimal Atomic Magnetometry for Practical Applications: Examining Scheme, Laser Source, and Vapor Cell Interplay

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Atomic magnetometers offer high sensitivity for measuring magnetic fields in areas such as biomagnetic monitoring, non-destructive testing, geological exploration, and fundamental physics research. Unlike superconducting quantum interference devices (SQUIDs), they do not require cryogenic operating temperatures, making them more practical for a range of real-world conditions. In addition, they typically surpass nitrogen-vacancy magnetometers (NVMs) in sensitivity. As industry increasingly demands compact, cost-effective, and robust solutions, optimizing the choice of OPM scheme, laser source, and vapor cell type becomes critical for meeting diverse operational constraints. Identifying optimal trade-offs is thus essential for transitioning these systems from the laboratory to real-world applications.

To explore the optimal balance of performance metrics for diverse applications, we compared four optically pumped magnetometer (OPM) schemes—Free-Induction Decay (FID), Nonlinear Magneto-Optical Rotation (NMOR), Amplitude-Modulated Bell–Bloom (AMBB), and a dual-beam amplitude-modulated dead-zone-free (DZF) approach—employing different laser sources (VCSEL, DBR, and ECDL) and vapor cell types (paraffin-coated, ˜50 torr neon, ˜50 torr nitrogen). Experiments were conducted under controlled conditions inside a four-layer magnetic shield to minimize external interference. We systematically measured magnetometer performance at an applied field of 1 μT, focusing on key metrics such as sensitivity, bandwidth, dynamic range, and overall system complexity, and obtained sensitivity results ranging from hundreds of fT/√Hz to hundreds of pT/√Hz.

The results underscore important trade-offs in sensitivity, bandwidth, dynamic range, and complexity across different OPM implementations. They also provide guidelines for selecting an optimal configuration tailored to various measurement requirements in atomic, molecular, and optical physics, as well as in on-site applications

Poster Session and Buffet / 25

Forward Modelling in MagnetoEncelphaloSpinography

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Optically Pumped MagnetoEncephaloSpinography (OP-MSEG) offers a promising new avenue for concurrent non-invasive imaging of spinal cord and brain activity. However, the accuracy of source localisation in the cord critically depends on the quality of the forward model; particularly given the spinal cord's complex geometry, deep location, and conductive environment. In this study, we evaluate how anatomical and numerical modelling choices determine forward model accuracy.

A previous simulation study has shown that the inclusion of bone in the anatomical model considerably affects the expected OPM signal1, a phenomenon not otherwise observed in traditional brain MEG. Hence, we look to compare three models featuring different representations of the vertebral column: a homogeneous toroidal model, an inhomogeneous toroidal model, and a continuous vertebral structure. Two forward modelling frameworks, finite element (FEM) and boundary element (BEM) methods, are used to generate magnetic field predictions under multiple dipole orientations and positions within a segmented spinal cord mesh. Our initial results show that the choice of bone model significantly influences the predicted field strength and topography.

To validate the forward models, we are currently acquiring anatomical and functional data with a novel, custom-built scanner cast made for a single subject. This has been developed to ensure consistent and reproducible co-registration between the OPM sensor array and spinal cord anatomy, enabling precise spatial alignment across modalities. Validation of the forward models will be performed by comparing predicted and measured magnetic field topographies using quantitative similarity methods.

The aim is to identify a forward model that balances anatomical accuracy with computational efficiency, which also provides a suitable comparison to experimental data. Thereby enabling robust, scalable OP-MESG pipelines suitable for use across participants and research sites.

1. George C. O'Neill, Meaghan Spedden, Maike Schmidt, Stephanie Mellor, Matti Stenroos, and Gareth R. Barnes. Volume conductor models for Magnetospinography. bioRxiv, 2024. Preprint

OPM Development III / 26

Metastable Helium-4 OPMs : current status and perspectives

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Optically-pumped magnetometers (OPM) using metastable helium-4 species allow real-time, space-resolved vector measurement of magnetic fields at room temperature. Moreover, the bandwidth of this kind of sensors –up to 2 kHz– covers the whole emission of the human brain. Hence, this technology proves very promising for magnetoencephalography (MEG) applications while minimizing patient discomfort caused by excessive heating or cooling of the sensors 1. Although the signal-to-noise ratios in field recordings already match the ones of SQUID systems 2, we continue the efforts to improve the intrinsic noise of these OPMs 3.

In this sense, we started by characterizing its sources. They include the phenomena in the plasma discharge –necessary to produce the metastable atoms– and the noises from the laser –that optically pumps the metastable atoms. We present measurements of the noises originated from both these sources and demonstrate their respective contributions to the total intrinsic noise of the sensor. Ways for improving the signal-to-noise ratio of our technology are also discussed.

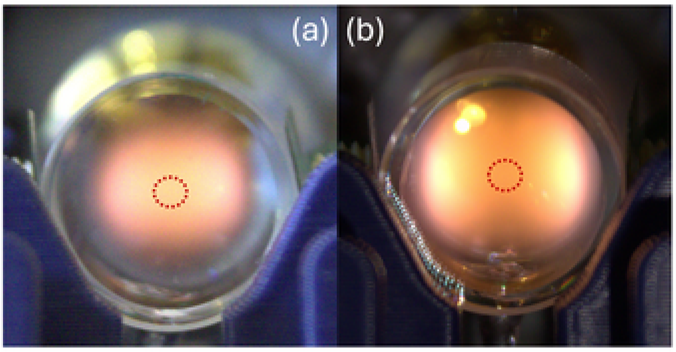

Figure 4: Helium plasma in the glass cell for (a) weak and (b) high plasma supply voltage

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Poster Session and Buffet / 27

Towards Magnetic Induction Tomography of low conductivity materials using OPMs

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Co-authors: Adam Taylor [1]; Alister Davis [1]; Chris Morley [1]; James Sharp [1]; Mark Fromhold [1]; Niall Holmes [1]; Thomas Smith [1]

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Background: Magnetic Induction Tomography (MIT) is an electromagnetic imaging technique that maps a material's electrical conductivity by inducing eddy currents via a primary oscillating magnetic field. The resulting secondary magnetic fields from the eddy currents are measured for image reconstruction and object characterisation. Performing MIT on low-conductivity samples (e.g. human tissue, saline) is valuable but challenging due to weak secondary fields. Optically pumped magnetometers (OPMs), known for high sensitivity, show promise for such applications. We present progress towards an OPM-MIT system for low-conductivity samples, including image reconstruction algorithm development and simulations of secondary field magnitudes.
Methods: Using a Minimum Norm Estimation (MNE) algorithm, we reconstructed images from numerically simulated (via COMSOL) secondary fields. Samples included a 1-cm copper cube (conductivity = 5.998×107 S/m) and copper 'letters'. A magnetic dipole forward model estimated the dipole source distribution matching the secondary field maps. We also simulated secondary fields from a 1-cm cube with conductivity of 10 S/m.
Results: Samples were placed on a 5-cm square grid. Secondary fields were measured on a 1-cm resolution grid located 1 cm from the sample, with a forward model based on 1-mm pixels. MNE-derived images correlated well with the ground truth (coefficient ≈ 0.8). Simulations indicated the expected linear relationship between conductivity and secondary field magnitude. A 150 μT primary field induced a 300 fT secondary field at 6 mm from a 10 S/m sample.
Outlook: Results suggest MIT of low conductivity samples to be possible using OPMs. Our simulation-based imaging algorithm will next be validated experimentally using a copper sample and fluxgate magnetometer. We will also use insights to advance the design, development and realisation of an OPM-MIT system.

Poster Session and Buffet / 28

Magnetic shielding performance with spray coating

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This contribution reports on a new spray-coating approach for magnetic shielding materials aimed at improved low-frequency field measurements with optically pumped magnetometers. Building on earlier investigations, we have successfully spray coated pure iron and Invar onto Aluminum substrates, and ongoing work explores spray coating of mu-metal. A 3-axis Helmholtz coil setup in a magnetically shielded room was used to measure the shielding effectiveness, comparing the spray-coated samples with references such as fully enclosed and partially open mu-metal cubes. Current efforts focus on extending the method to multi-layered shielding constructs of more complex structures, to achieve lightweight, flexible shielding solutions compatible with precise magnetometry.

Poster Session and Buffet / 29

Development of an NMOR gradiometer for human brain stimulation

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In recent work 1, we showed the efficacy of an intrinsic axial gradiometer for the detection of human biomagnetism. We now present the next generation of this sensor, which employs the nonlinear magneto-optical rotation effect. By using simplified integrated optics, printed circuit boards, and a modular design, we have improved the mechanical rigidity and decreased the standoff from the human scalp. Due to these factors, the extraction of human brain signals is more robust and can be achieved with fewer trials. The sensitivity has remained stable at 15 fT/√Hz/cm, which, at a baseline of 5 cm, corresponds to 70 fT/√Hz in absolute units. The purpose of this sensor is to combine it with transcranial magnetic stimulation, in which a strong and fast (around 0.1 T/μs) magnetic field is delivered to the brain to induce neural currents. We will describe the setup used to perform the experiment and we hope to have preliminary results by the time of the WOPM meeting.

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Poster Session and Buffet / 30

Effects of power broadening on NMOR of alkali atoms with partially resolved hyperfine structure

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This study investigates the effects of power broadening on nonlinear magneto-optical rotation (NMOR) magnetometers. As the laser power increases, the interference between two partially resolved transitions of 87Rb induced by velocity-changing collisions can be exacerbated by power broadening, resulting in a reduction
of the rotation rate, and the shift of the optimal laser frequency corresponding to the maximum rotation rate. The theoretical model of NMOR is established using a four-level double ⊠ scheme, which takes into account power broadening effects, and experimentally studied in a single-beam NMOR magnetometer with a buffer-gas filled cell. The results indicate that the significant enhancement in rotation rate can be achieved by tuning the laser frequency to the optimal detuning based on our model. This study holds considerable importance for the improvement of magnetic field sensitivity in NMOR magnetometers.

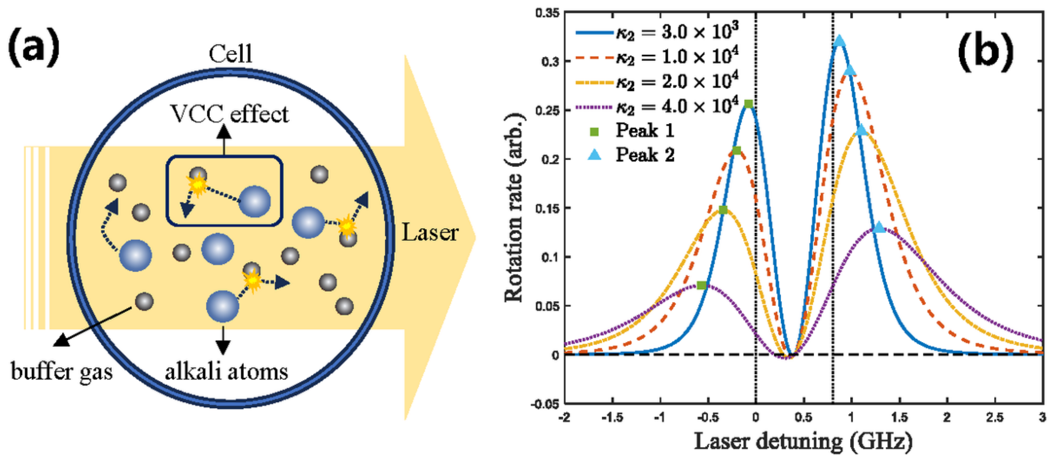

Figure 5: (a) VCC effects in buffer-gas filled vaper cells.(b) Simulations of the rotaion rate spectra for different laser power

OPM Applications II / 31

Noninvasive, multichannel nuclear magnetic resonance chemical analysis via OPM arrays in the zero- to ultralow-field regime

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We leverage an array of commercially available OPMs to perform sensitive, high throughput nuclear magnetic resonance (NMR) on multiple chemical samples simultaneously for the first time by leveraging the zero- to ultralow-field (ZULF) regime, with proof-of-principle demonstrations suggesting the feasibility of constructing a 100-OPM-channel device. This regime offers many advantages over conventional NMR methods, such as significantly relaxed magnetic field homogeneity requirements, which significantly mitigates cost. Stable operation for weeks without field drift or need for recalibration has also been achieved, along with the ability to detect analytes non-invasively through various materials, such as metal. We demonstrate significant improvements in sensitivity, namely, the ability to measure "off the shelf"samples without isotopic enrichment, with performance similar to commercial benchtop systems, addressing a critical barrier to real-world application. Lastly, ZULF NMR is a noninvasive chemical fingerprinting tool that can potentially yield precise through-bond coupling values for molecular identification when paired with ab initio calculations.

Poster Session and Buffet / 32

Mechanism of circular dichroism under magnetic-light- atom interaction

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In the research of the interaction between light and atoms, optical ellipticity is a key parameter to characterize the pump and absorption process [1,2]. It was generally believed that ellipticity only originated from the the interaction between magnetic fields and polarized alkali metal atomic ensembles in previous researches [3,4,5]. In this research, a new mechanism of circular dichroism caused by the interaction between the probe light and the polarized atom ensemble in the SERF regime is revealed by establishing a quantum mechanical model based on the density matrix, combining with Maxwell equations. The experiment results indicates that the interaction between magnetic field, alkali metal atomic ensemble and probe light is a new source of ellipticity. We prove that ellipticity is an inherent property of atomic ensemble, and is independent of external excitation conditions. This research verifies the coupling mechanism of the resonance light and the atomic ensemble in SERF magnetometer and provides a new theoretical framework for ultra-high sensitivity atomic magnetometer and multi physical field coupling measurement.

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2X. Fang et al., "Accurate and fast measurement of alkali-metal and noble-gas atoms spin polarizability based on frequency response in SERF co-magnetometer,"Measurement, vol. 222, Nov. 2023, Art. no. 113562.
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Poster Session and Buffet / 33

Phase-dependent CMRR enhancement method for optically pumped magnetic gradiometers

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Optically pumped magnetometers (OPMs) offer significant advantages for biomagnetic measurements such as magnetoencephalography (MEG), owing to their high sensitivity, room-temperature operation, and potential for wearable configurations. In these applications, gradiometric measurement serves as an effective method to suppress common-mode environmental noise. However, it is difficult to make the two channels in a gradiometer perform identically, and precisely adjusting system parameters remains a challenge, which limits the common-mode rejection ratio (CMRR).

To overcome this limitation, we propose a method to improve the CMRR of OPM gradiometers, based on analyzing and controlling the phase-frequency response differences between the two channels. The phase differences between the two channels would degrade the CMRR, as they reduce the consistency of the responses. We model the relationship between the phase-frequency response of the gradiometer and the relaxation rate of the cell and the remanence along the pump axis. This model reveals a phase intersection point at which phase responses between two channels are aligned, leading to the enhanced CMRR. By precisely adjusting the magnetic field along the pump axis, this intersection point can be controlled, thereby enabling optimization of the frequency band in which maximum CMRR is achieved. As a result, the average CMRR within 1-50 Hz frequency band is improved by more than one order of magnitude, exceeding 2000. This method enables efficient performance enhancement without additional components and offers flexibility for various application scenarios.

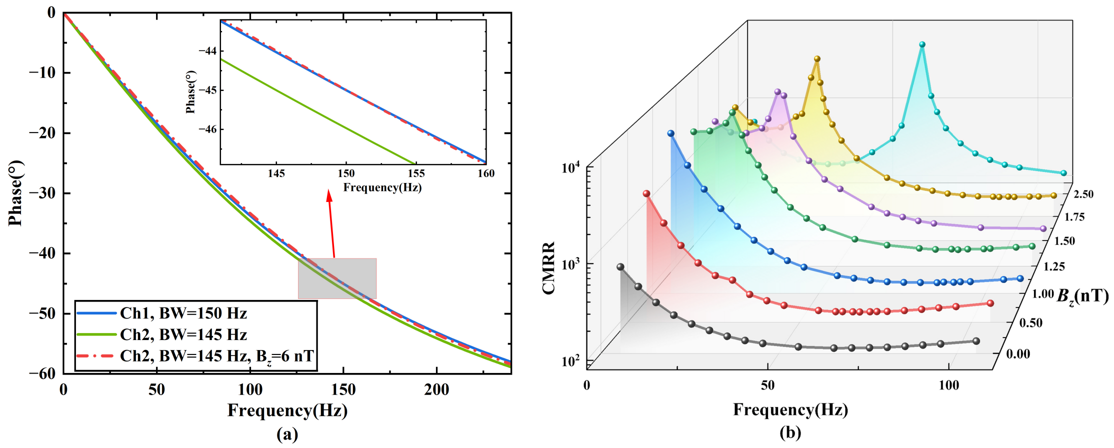

Figure 6: (a) Simulated phase-frequency response of OPMs with different bandwidths. (b) Variation of CMRR with signal frequency under different Bz.

Poster Session and Buffet / 34

In-Situ Vapor Cell Temperature Control in OPMs via Transmitted Light Signal Feedback

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The modulated single-beam Spin-Exchange Relaxation-Free (SERF) optically pumped magnetometers (OPMs) hold significant promise for applications in biomagnetic measurements. Achieving the SERF regime requires a high atomic number density, which necessitates a stable thermal control system for the vapor cell. Conventionally, the vapor cell temperature is measured by the platinum resistance sensor. However, its measurements are non-in-situ and sensitive to positioning. In this study, we demonstrate an approach to control the vapor cell temperature by utilizing the ratio of the second harmonic to the DC component of the transmitted light signal as a feedback parameter for closed-loop temperature regulation. This method enables real-time, in-situ temperature control using the OPM's optical signal, while exhibiting reduced susceptibility to fluctuations in incident light power.
Experimental results as shown in Fig. 1(a) indicate that this ratio-based feedback is less affected by variations in incident light compared to the DC signal feedback alone. We conduct long-term testing under externally applied disturbances, demonstrating the system's stability and robustness, as shown in Fig. 1(b). Taken together, the results in Figs. 1(a) and 1(b) confirm that this thermal control method effectively suppresses the influence of incident light power fluctuations on optical temperature sensing and satisfies the thermal stability requirements of SERF OPMs, with resistance to external disturbances.

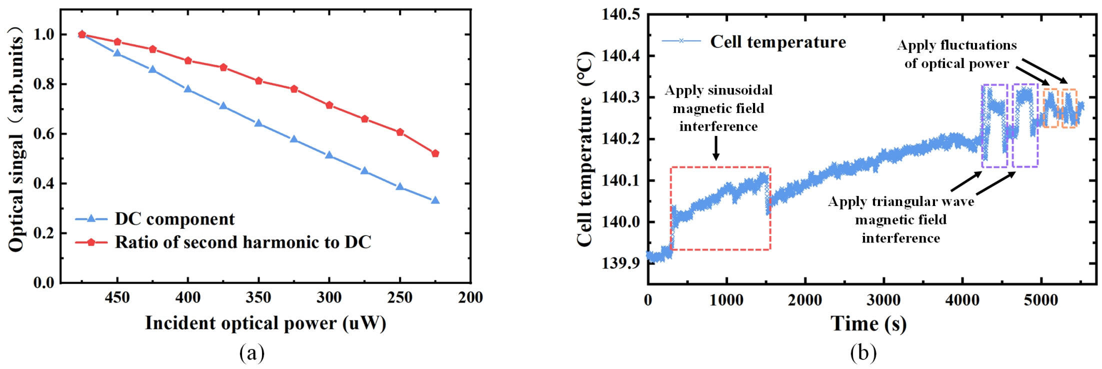

Figure 7: (a)The variations of the second harmonic to DC ratio and the DC component itself with the incident light power. (b)Long-term evaluation of thermal control performance under external disturbances.

Poster Session and Buffet / 35

Molecular Dynamics Optimization of OTS Coatings and Implications for High-Precision Atomic Magnetometry

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Molecular Dynamics Optimization of Multilayer OTS SAMs Cells for Enhanced Performance in Single Beam SERF Magnetometers

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The development of high-performance octadecyltrichlorosilane (OTS) SAMs is crucial for mitigating alkali-metal spin relaxation and enhancing the sensitivity of spin-exchange relaxation-free (SERF) magnetometers. In this work, we employ molecular dynamics (MD) simulations to investigate the structural, interfacial, and dynamical properties of OTS SAMs, focusing on optimizing their anti-relaxation behavior. By systematically tuning key simulation parameters, including adsorption energy, wettability, and atomic interaction dynamics. Our findings provide a comprehensive framework for the rational design and optimization of OTS SAMs, paving the way for next-generation atomic magnetometers with enhanced stability and prolonged coherence times. Furthermore, we discuss the broader implications of these advancements in quantum sensing and precision measurement applications.

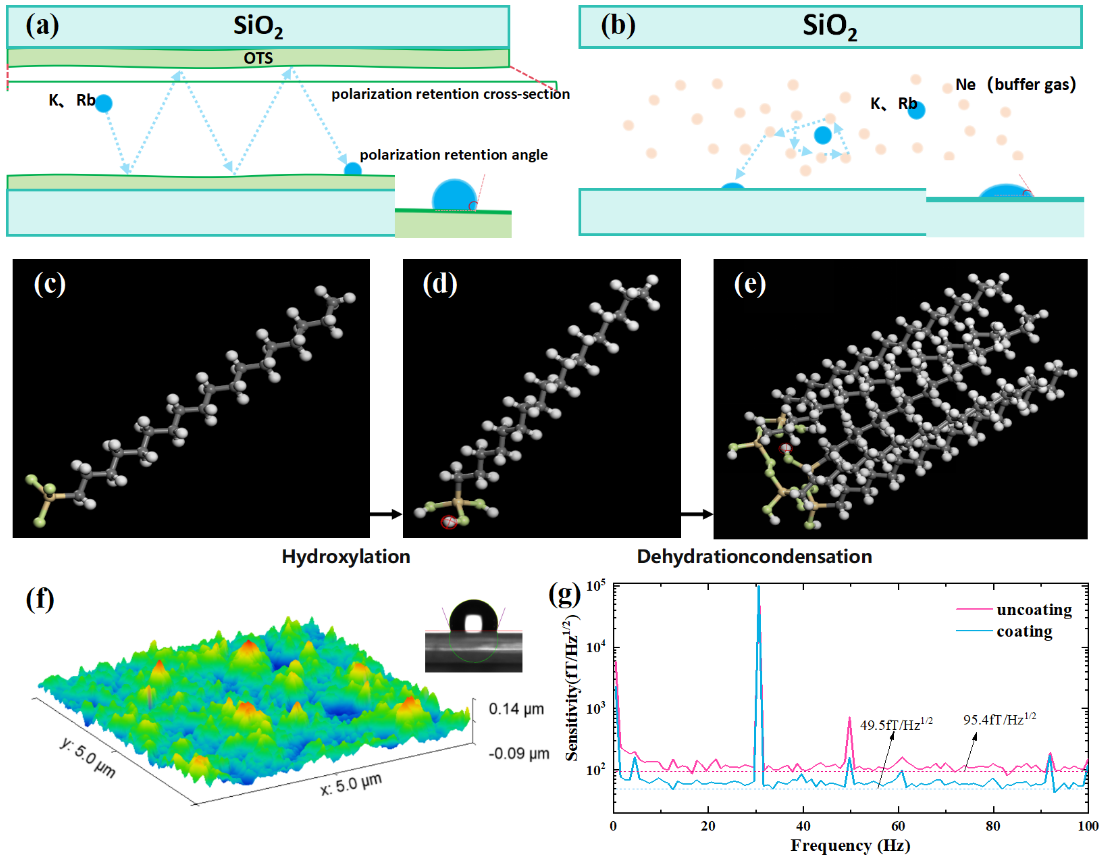

Figure 8: (a) Relaxtion of coating cell, (b) relaxation of uncoating buffer gas cell,the molecular cross linking process of OTS : hydroxylation(c to d) and dehydration condensation(d to e), (f) AFM and contact angle test of OTS SAMs, (g) sensitivity of coating and uncoating magnetometer

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Poster Session and Buffet / 36

Mr Qi

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Co-authors: Jia ; Song

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Optically pumped magnetometers (OPMs) based MEG has been widely used in biomagnetic imaging applications with the advantages of closer distance to the scalp, mobile measurements, and high sensitivity. However, it may suffer from angular errors of sensitive axis due to low frequency remnant magnetic fields or magnetic field crosstalk from adjacent sensors, which is determined by the requirement of SERF mechanism for zero magnetic field. The orientation of the sensitive axis of the magnetometer may change caused by the DC remnant magnetic fields orthogonal to the OPM's nominal sensitive axis. In inverse problem, the estimation of source locations and time series signal depends on the accurate estimation of the lead field matrix which requires complete geometric parameters of the OPM array, including sensor positions and sensitivity axis directions. Angular error in sensor orientation propagates systematic errors in the forward solution, which will considerably lead to source localization error and impact the spatial resolution of inverse algorithms (e.g. beamforming). Here, we characterized the effect of angular error on the spatial resolution in a typical OPM array to pave the way for understanding the corrective measures necessary for source reconstruction.
Numerical simulations based on realistic head models were conducted to quantify the capacity of OPM arrays to distinguish two adjacent sources. A sensor array was constructed with 6 mm scalp-to-array distance and 30 mm inter-sensor spacing. Two distinct OPM array configurations of single axis or dual axis were implemented. Two orthogonal source time series signals were assigned to two sources with a distance of 6 mm on the MNI template cortex mesh from SPM12 toolbox. Random angular offsets were applied to each OPM's sensitive axis to model the angular error. Then the correlation coefficient between reconstructed source time series can be used as an indicator of spatial resolution of OPM-MEG systems.
Results demonstrated that the effects of angular errors on spatial resolution of single-axis and dual-axis OPM arrays are similar. Correlation values increase with increasing angular error. 2° angular error will make it difficult to distinguish some source pairs. The simulation results also show that the presence of an angular error has a more significant effect on the spatial resolution at higher signal-to-noise ratios.

Poster Session and Buffet / 37

Low-crosstalk triaxial dynamic measurement method for wearable OPM-MEG

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Optically pumped magnetometers (OPMs) have significantly advanced the field of biomagnetic sensing, particularly in wearable applications such as magnetoencephalography (MEG). Triaxial measurement techniques further enhance the localization accuracy of these systems by capturing full vector information. However, the precision of triaxial OPM measurements is still constrained by two major issues: crosstalk introduced by multiple modulated magnetic fields and interference from low-frequency ambient magnetic field fluctuations.

To address these limitations, we propose a dynamic triaxial magnetic field measurement method that employs a single modulated magnetic field to reduce crosstalk. Additionally, it incorporates a closed-loop control system to suppress low-frequency magnetic field fluctuations under moving experiments. Experimental results demonstrate that the proposed method achieves measurement sensitivities of 20.3, 9.6, and 42.2 fT/Hz$^{1/2}$ along the x, y, and z axes, respectively. Moreover, the approach reduces scale factor fluctuation by 95.2% and decreases simulated MEG amplitude error by 64.2% under magnetic interference conditions. These improvements not only enhance measurement accuracy but also expand the practical potential of high-density wearable OPM-MEG systems.

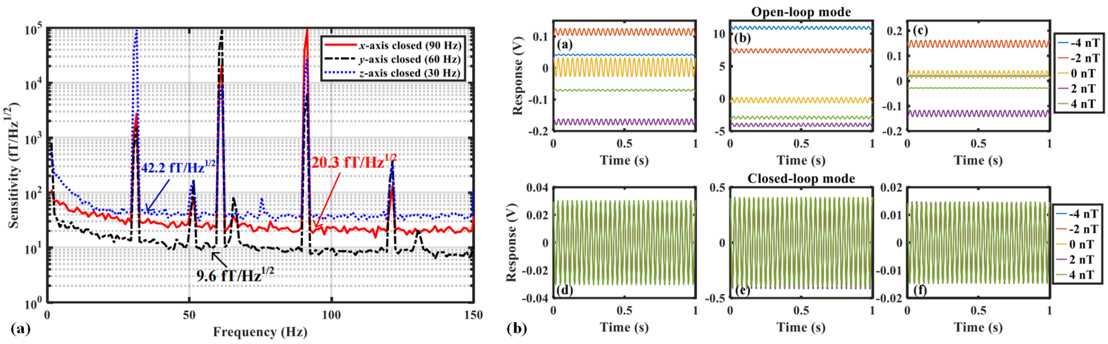

Figure 9: Results of triaxial dynamic measurement. (a) The triaxial measurement sensitivities of an OPM in the closed-loop mode. (b) Measurements of sinusoidal calibration signals under residual magnetic field fluctuations.

Poster Session and Buffet / 38

Picotesla optically pumped magnetometer using a laser-written vapor cell with sub-mm cross section

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We demonstrate atomic spectroscopy and optical magnetometry with picotesla sensitivity using laser-written Rb vapor cells. The technology can be integrated with photonic structures and microfluidic channels in a single platform for lab-on-chip atomic quantum sensing.

MEG / 39

OPM-MEG versus SQUIDs MEG for object decoding via multivariate patter analysis

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Co-authors: Anna Kowalczyk [1]; Yu Sun [3]; Ole Jensen [4]

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Multivariate pattern analysis (MVPA) is a well-established method in functional neuroimaging, commonly applied to fMRI, MEG, and EEG data to classify spatial patterns of brain activity associated with different objects or experimental conditions. Optically pumped magnetometer (OPM)-based MEG systems have the potential to enhance MVPA performance, as they are theoretically shown to offer improved spatial specificity compared to conventional SQUID-based MEG systems 1. However, this theoretical advantage has yet to be confirmed experimentally.
In this study, we directly compared object decoding performance between an OPM-MEG system and a traditional SQUID-MEG system using an MVPA approach. Nine participants completed an object recognition task while brain activity was recorded in two modalities: picture stimuli and their corresponding written words 2. Each participant took part in two recording sessions—one using a 76-sensor OPM-MEG system (FieldLine Inc) and one using a conventional SQUID system (Elekta Neuromag system).
We applied MVPA to pairwise classify responses to objects on the screen using data from 68 magnetometers for both MEG systems. Our results show that, for pictured and word-based stimuli, classification accuracy was consistently higher with OPM-MEG compared to SQUID-MEG. This provides experimental evidence supporting the expected spatial advantages of OPMs for decoding patterns of brain activity.

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Poster Session and Buffet / 40

Investigation of HTS Magnetic Shielding for Ultralow Magnetic Fields in Precision Measurement Applications

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Co-authors: Danyue Ma [1]; Faming Wang [1]; Haoran Lv [1]; Xiujie Fang [1]; Yanan Gao [1]; Yangzhi Xue [1]; Yaqi Zhang [1]

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Abstract：With the rapid advancement of cutting-edge fields such as quantum precision measurement and biomagnetic sensing, increasingly stringent requirements are being placed on the suppression of ambient magnetic fields. The sensitivity improvement of atomic magnetometers is currently limited by the residual magnetization and intrinsic magnetic noise of conventional soft magnetic shielding materials. In this study, we propose a novel high-temperature superconducting (HTS) magnetic shield and investigate its performance in ultra-low magnetic field environments, aiming to meet the demands of next-generation quantum sensing and biomedical imaging applications.
A theoretical model based on the London equations was established to simulate the magnetic shielding behavior of HTS materials in extremely weak magnetic field environments. The model's results were compared with those obtained from the widely used critical state model under the same conditions. Finite element simulations were conducted to systematically analyze the influence of key structural parameters, including aspect ratio and wall thickness, on the shielding effectiveness. Furthermore, an experimental platform for low-temperature superconducting magnetic shielding was developed, and experimental validation was carried out at 77 K. The experimental results show good agreement with the simulations, confirming the validity of the model.
This work provides valuable insights for the design of HTS magnetic shielding structures in sensitive magnetometry systems and offers a promising approach for realizing ultra-clean magnetic environments in precision measurements.
Keywords: High-temperature superconductors; Magnetic shielding; London equation; Ultralow magnetic field; Atomic magnetometry; Precision measurements

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Optimization of Magnetic Field Residual and Gradient in Permalloy-Ferrite Shielding System for SERF Magnetometer Based on Electro-Thermal Demagnetization

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Abstract—Soft magnetic materials, characterized by high magnetic permeability, are typically utilized in the magnetic shields. Among these, a composite shielding system comprising outer layer Permalloy and inner layer manganese-zinc (Mn-Zn) ferrite has demonstrated exceptional performance in providing an extremely-low magnetic interference environment for spin-exchange relaxation-free (SERF) magnetometers, owing to its synergistic combination of high shielding efficiency and low magnetic noise. This magnetic shielding system gets magnetized over time and during disassembly and assembly, and needs to be demagnetized regularly. To minimize the magnetic field residual and gradient introduced by magnetic shielding system, and further improve the sensitivity of the magnetometer, alternating current (AC) electric demagnetization method is commonly employed to achieve effective degaussing. However, compared to permalloy, large-scale ferrite shields have higher coercivity, electric demagnetization methods are not effective enough, limiting the application in large electromagnetic shielding systems and high-precision instruments. Therefore, electro-thermal demagnetization method is proposed. Thermal demagnetization is used for ferrite, while multi-layer permalloy continues to use electric demagnetization. A double-layer counter-wound non-magnetic heating film to heat the ferrites is designed to suppress the magnetic field introduced by itself. The effectiveness of the method is verified through theoretical modeling, simulation analysis and experiments. Parameter optimization is also conducted. The results indicate that, within ±15 mm of the center, the electro-thermal demagnetization reduces the residual magnetic field to below 0.2 nT with a gradient less than 0.015 nT/cm (radial) and below 0.05 nT with a gradient less than 0.013 nT/cm (axial). Compared to the traditional electric demagnetization method, the residual magnetic field and its gradient of electro-thermal demagnetization are reduced more than 5 and 10 times respectively. This article supports the application of large-scale Permalloy-ferrite magnetic shields for measurement instruments especially in atomic magnetometers and in cutting-edge physics research.
Key Words —Electro-thermal demagnetization, Ferrite, Magnetic shielding, Permalloy, SERF magnetometer

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Measurement of Spin Polarization in SERF Hybrid Optical Pumping Atomic Magnetometer via the Steady-State Response to the Triaxial Magnetic Field

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In SERF atomic magnetometers, the spin polarization of alkali-metal atoms is a critical parameter affecting the signal-to-noise ratio. The signal of the magnetometer is optimal for a particular spin polarization, and higher spatial uniformity of spin polarization enhances the signal. Hybrid optical pumping is a method to improve the spatial uniformity of spin polarization. The signal of the hybrid pumping magnetometer is influenced by multiple parameters, including temperature, alkali-metal density ratio, pump light power and frequency, and probe light power and frequency. Therefore, precise measurement of the spin polarization and its spatial distribution in SERF hybrid pumping magnetometer is essential to optimize its response signal.

This study proposes a novel method for measuring alkali atomic spin polarization based on the steady-state response of a SERF hybrid optical pumping atomic magnetometer to the triaxial magnetic field. First, different DC magnetic fields were applied in the x- and y-axes and y- and z-axes, and the total relaxation rate at a specific position within the vapor cell was obtained using the ratio of the system's steady-state responses under these two conditions. Next, the transfer coefficient between spin polarization along the probe light direction and the steady-state response was calculated, where the optical depth of the probe light was utilized to derive alkali-metal atomic density, compensating for temperature gradient effects. Finally, a DC magnetic field was applied along the sensitive axis of the magnetometer, and the spin polarization was obtained using the steady-state response, transfer coefficient, and total relaxation rate. The advantages of this method include eliminating the need for optical field manipulation or large magnetic fields, reducing errors from residual fields, coil constant calibration, temperature gradients, and by spatially displacing the probe light enables the acquisition of the spatial distribution of spin polarization along the propagation direction of the pump light. Experimental results aligned with simulations, with a maximum deviation below 6%. The expanded uncertainty of measurements ranged from 1.1% to 9.8%. This method provides precise measurement of atomic spin polarization, which is of significant importance for enhancing the sensitivity of SERF hybrid pumping atomic magnetometers and laying the foundation for ultra-weak magnetic field detection.

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FPGA-Based Broadband Pumping in SERF Atomic Magnetometers

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Atomic magnetometry based on the spin-exchange relaxation-free (SERF) effect has emerged as a key technology for high-precision magnetic field measurements due to its ultrahigh sensitivity. A critical factor in enhancing the sensitivity of SERF magnetometers is achieving uniform spin polarization in high-density alkali-metal vapor. However, conventional narrow-linewidth optical pumping often leads to polarization gradients along the pump beam direction under high atomic density, due to incomplete polarization, which fundamentally limits device performance. In this work, we propose a broadband optical pumping scheme using external-cavity electro-optic phase modulation. An FPGA-controlled radiofrequency modulation system is employed to spectrally broaden the laser, and the relationship between phase noise and spectral width is quantitatively analyzed based on the Wiener-Khinchin theorem. The resulting broadband laser source exhibits strong noise suppression and significantly improves spin polarization homogeneity. Experimental results show more than 40% enhancement in spin polarization uniformity, a 4.3-fold reduction in optical frequency noise, and a 54% increase in system response compared to unmodulated pumping. A sensitivity of 0.34 fT /√Hz is achieved at 30 Hz. This approach is readily extendable to other large-volume atomic ensembles requiring homogeneous spin polarization, offering a powerful solution for next-generation biomagnetic sensing applications such as magnetocardiography and magnetoencephalography.
Keywords: SERF magnetometer; broadband laser; optical pumping; spin polarization uniformity; phase modulation; noise suppression; FPGA control

OPM Development I / 44

Uncovering the Hidden Variability and Challenges in SERF-OPMs Through Structured Magnetometer Benchmarking

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The emergence of Spin-Exchange-Relaxation-Free (SERF) Optically Pumped Magnetometers (OPMs), ranging from single-sensors to fully integrated multichannel systems, has opened new frontiers in biomedical applications and other sensing areas through remote and rapid magnetic field sensing. Without detailed manufacturer specifications, treating these sensors as black boxes can conceal critical limitations, particularly for medical end-users. Understanding the input-output behavior of each individual channel is essential to maintain signal integrity and future diagnostic reliability. This profound insight has emerged from systematic benchmarking studies and rigorous investigations involving Magnetoelectric (ME) sensors, underpinned by extensive fundamental research, accumulated expertise, electronics development, and valuable feedback from medical professionals 1.

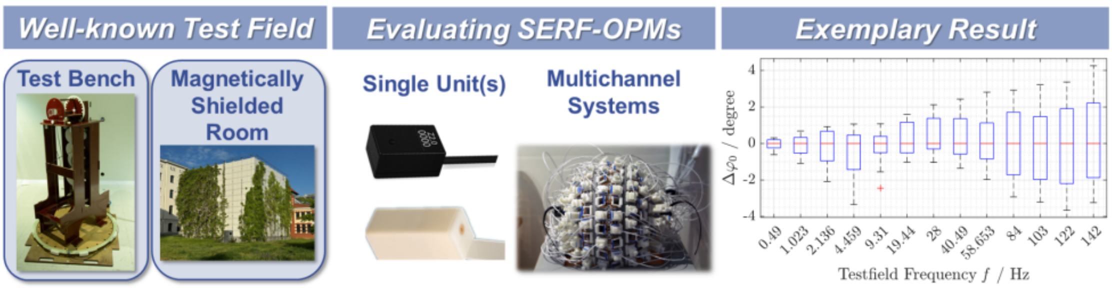

Figure 10: enter image description here

Figure 1: *Overview of our systematic approach for magnetometer characterization. Exemplary result showcase spread of intra-channel phase delays as a boxplot in one multichannel system (triaxial mode, closed-loop) for one axis; the red line denotes the median phase delay across 19 units operating in triaxial mode.*

In this contribution, we present a systematic approach for evaluating highly-sensitive magnetometers within the Berlin Magnetically Shielded Room 2.1 (BMSR-2.1) at the Physikalisch-Technische Bundesanstalt (PTB), Berlin, Germany. Central to this effort is our dedicated test bench (DALAC), which facilitates detailed assessment of key performance parameters within a well-characterized test environment and magnetic test field (cf. Fig. 1) 2. Using measurement data from commercially available multichannel SERF-OPM systems, we demonstrate the critical and broad importance of a systematic characterization approach in comparison with the biomagnetic gold standard given, SQUID. Besides sensitivity, bandwidth, linear range, gain stability, amplitude response flatness, and time delay are investigated, with particular attention to intra-channel variability (cf. Fig. 1). Without standardized characterization, sensor-specific influences on the sensed signal can compromise data integrity, posing serious risks in high-precision applications like MCG, MMG, MEG, and especially source reconstruction. Therefore, systematic characterization is essential for the reliable biomedical use of SERF-OPMs.

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Quantum and Fundamental / 45

Quantum enhancement in a multi-parameter quantum sensor.

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We study quantum enhancement of sensitivity and bandwidth using squeezed light in a multi-parameter quantum sensor, the hybrid rf-dc optically pumped magnetometer (hOPM) 1. Using a single-spin ensemble, the hOPM acquires both the dc field strength (scalar magnetometry) and resonantly detects one quadrature of the magnetic field at a programmed frequency (rf magnetometry). In contrast to scalar OPMs 2, the back-action evasion in the hOPM is incomplete, leading to a complex interplay between the three quantum noise sources in this system: photon shot noise, spin projection noise, and measurement back-action noise. We observe these interactions using squeezed light as a tool to control the distribution of optical quantum noise between polarization Stokes components, and the resulting effect on readout quantum noise and measurement back-action 3.

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OPM Development I / 46

Omnidirectional Diamond-Based Vector Magnetometers

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Vector magnetometers provide lots of information for applications that require analysis of magnetic source ranging from bio-imaging to geophysical exploration. Magnetometer based on nitrogen-vacancy (NV) centers in diamond, as an unprecedented combination of spatial resolution and magnetic sensitivity, however, normally need complex manipulation to distinguish the correspondence between field projections and NV axes1, or even unable to measure certain field directions2. We developed an omnidirectional vector magnetometry which combines precise measurements of full NV axes by few applications of magnetic fields, and logical solving the correspondence and readout of overlapped resonance frequencies by selectively magnetic manipulating NV ensembles, ensuring a good detection accuracy in all directional detections. This method is not only intelligent and convenient, but also capable of measuring dead zones due to overlapping. With conventional laboratory setup and commercial NV samples, we achieved an angular resolution around 0.02° in all direction of magnetic field and an angular error around 0.2°. The angular resolution is expected to reach arc seconds by optimization of experimental conditions. This method can improve the universality and practicality of NV magnetometers, and promote the development of NV towards industrial magnetometers.

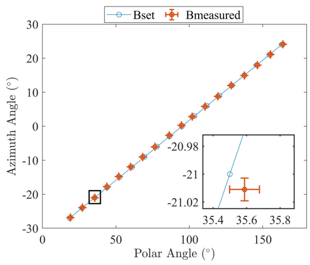

Figure 11: Comparison of set and measured directions of magnetic fields

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Poster Session and Buffet / 47

Single-beam Triaxial Spin-exchange Relaxation-free Magnetometer

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Unlike electrical signals, magnetic signals are not affected by the biological tissues because of the nearly homogeneous permeability. Therefore, magnetoencephalography (MEG) is more suitable for detecting biological phenomenon. In the past several decades, superconducting quantum interference device (SQUID) magnetometers are most commonly used for MEG. However, the SQUID magnetometers would not work unless
the superconducting circuits are housed in the liquid-helium-cooled dewar. The cryogenic cooling brings some significant problems 1. Optically pumped atomic magnetometers in the spin-exchange relaxation-free (SERF) regime have attracted significant attention 2. Compared with the SQUID magnetometers, SERF magnetometers have the sensitivity comparable to that of the SQUID magnetometers but do not need the cryogenic condition. Substantial research efforts have been devoted to improving the performance of SERF magnetometers. Recently, one of the hot research topics is how to realize the three-axis magnetic field measurement. It is helpful to obtain the complete vector information of the magnetic field.
Here, we propose and experimentally demonstrate two novel schemes to achieve measurement of three-axis vector magnetic fields. One approach employs a specially designed triangular prism-shaped vapor cell 3. By reflecting the light beam in the cell chamber under high pressure, the atoms before and after reflection are polarized along two different directions. It is as though two dual-axis parametric resonance magnetometers are combined in the same vapor cell. A sensitivity of 40 fT/Hz1/2 in x-axis, 20 fT/Hz1/2 in y-axis, and 30 fT/Hz1/2 in z-axis is achieved. Another scheme is by utilizing a dual-resonance effect, which is discovered for the first time in the SERF regime. This is an easy-to-implement engineering solution. On the basis of a dual-axis parametric resonance magnetometer, as long as the rotating field frequency is reduced from kilohertz to hundreds of hertz, then Mz resonance is excited synchronously, and hence the dual-axis magnetometer can be upgraded with three-axis measurement capabilities. Eventually, we can attain magnetic field sensitivities of about 40 fT/Hz1/2 in x- and y-axes and about 50 fT/Hz1/2 in the z-axis [4].

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OPM Development III / 48

Miniaturized and Integrated Optically Pumped Magnetometer for Biomedical Applications

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We present a compact and integrated optically pumped atomic magnetometer (OPM) developed for high-sensitivity biomedical applications. This device, based on a Spin-Exchange Relaxation-Free (SERF) atomic magnetometer configuration, demonstrates a sensitivity of 20 fT/√Hz with a bandwidth of 1 to 80 Hz. The miniaturization of the magnetometer is achieved through the integration of an elliptically polarized single-beam optical path, utilizing a 5 mm × 5 mm × 5 mm Rb vapor cell. The compact design of device, with a total volume of 0.45 cm^3, allows for flexible deployment in various biomedical scenarios, including wearable applications. In experimental setups, the device is positioned within 4 mm of the biological tissue, ensuring optimal signal acquisition.
Our system has been successfully applied to non-invasive magnetoencephalography (MEG) in small animals, detecting rat auditory evoked magnetic fields with high fidelity[1,2]. Additionally, the magnetometer has been utilized for real-time monitoring of drug-conjugated magnetic nanoparticles (Fe3O4) in live mice, facilitating the assessment of drug release dynamics[3,4]. This capability has proven invaluable in drug delivery research and monitoring of biophysical processes in vivo. Furthermore, our device demonstrated its potential in studying neural activity in Drosophila, detecting oscillatory brain activity associated with visual salience. Finally, we presented a brain-computer interface (BCI) approach that uses our OPMs-based MEG associated with motor imagery (MI) for the synchronous operation of a brain controlled virtual drone in three-dimensional space [5].
The compact and portable nature of the developed OPM, along with its high sensitivity and non-cryogenic operation, make it a promising tool for advancing biomedical research, including applications in neuroscience and drug monitoring. Future work will focus on optimizing the sensor array for multi-channel measurements, obtaining the complete vector information of the magnetic field and enhancing real-time data processing to accommodate dynamic biomedical environments.

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Poster Session and Buffet / 49

Towards quantum enhanced optically pumped magnetometer at Earth's magnetic field

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We describe progress toward quantum enhancement of an optically pumped magnetometer (OPM), operating around Earth's magnetic field. We demonstrate back-action evading scheme with sub-pT/vHz quantum-noise-limited sensitivity, for frequency and amplitude modulation schemes. We also aim to demonstrate the quantum advantage of spin squeezing in highly polarized atomic ensembles within microfabricated isotopically enriched 87Rb cells. This work represents a step forward in developing compact and highly sensitive magnetometers, with potential applications in fundamental physics experiments and field-deployable precision sensing technologies.

Poster Session and Buffet / 50

Sensitivity Improvement of a 4He Optically Pumped Magnetometer in the RF band

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Sensitivity Improvement of a ^{4}He Optically Pumped Magnetometer in the RF band

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High-sensitivity detection of radio-frequency (RF) magnetic fields is critical for various applications, from radio communication to fundamental physics experiments. Ultra-low field MRI (ULF-MRI) with the static magnetic field less than 10 mT, in particular, demands sensors capable of operating with high sensitivity in the 100 kHz to 400 kHz range 1. Optically pumped magnetometers (OPMs) are promising candidates for high-sensitivity RF magnetic field detection. Previous studies have shown that the OPMs using alkali metal atoms exhibit high sensitivity for RF magnetic field detection, but their operation typically requires heating and careful management of spin-exchange relaxation in static magnetic fields 2. Our research focuses on OPM using ^{4}He (^{4}He-OPM), which operates without heating and offers a broad frequency range. While our previous work achieved a noise floor of 90 fT/Hz$^{1/2}$ at 100 kHz, sensitivity decreased at higher frequencies 3. In this study, through adjustments in the magnetic field configuration, we improved the sensitivity of ^{4}He-OPM for higher frequencies. Specifically, we achieved a noise floor of 13 fT/Hz$^{1/2}$ at 300 kHz. In addition, we will show the potential of ^{4}He-OPM for high-sensitivity detection at higher frequencies for applications such as ULF-MRI.

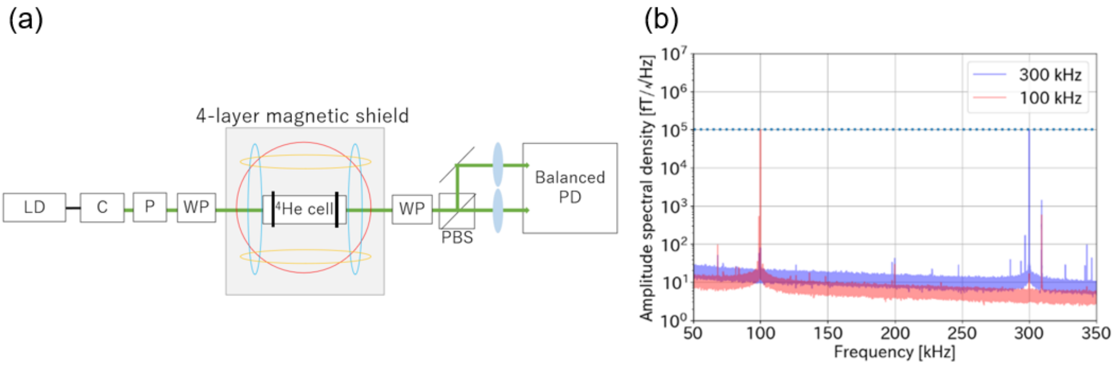

Figure 12: fig.1

Figure 1: (a) Schematic diagram of ^{4}He-OPM experimental setup. LD: laser diode; C: collimator; P: polarizer; WP: half-wave plate; PD: photo diode. (b) Amplitude spectral density for 100 pT$_{\mathrm{rms}}$ sinusoidal signals applied at 300 kHz and 100 kHz.

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Poster Session and Buffet / 51

Towards OPM-MEG in a single MuMetal layer magnetically shielded room

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Co-authors: Daniel Ferring [1]; Ashley Tyler [2]; Ryan Hill [3]; Joseph Gibson [1]; Lukas Rier [3]; Samu Taulu [4]; Bartel van der Veek [2]; Vishal Shah [5]; Matthew Brookes [3]; Richard Bowtell [1]; Niall Holmes [3]

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Background:
Magnetoencephalography (MEG) systems using optically pumped magnetometers (OPMs) require magnetically shielded rooms (MSRs); typically built from 2–5 layers of high-permeability material (e.g., MuMetal) and a conductive layer (e.g., copper) to block external magnetic fields. While effective, current MSRs are heavy (2,500–13,000 kg) and difficult to install (>3 m high), limiting OPM-MEG deployment. OPM-MEG has been demonstrated in MSRs with one MuMetal and one copper layer 1 but removing the copper would further cut costs and simplify installation.

Method:
We built a MSR using a single 1.5 mm-thick MuMetal layer, with an internal/external footprint of 1.3×1.3/1.6×1.6 m², a height of 2/2.5 m, and a weight of 1,100 kg—making it compatible with most rooms and floors.

Results:
Fluxgate measurements show a static field of 223 nT (52 dB shielding relative to the unshielded measurement) and baseline noise of 4.5 pT/√Hz (>24.8 dB). The largest AC spike is the 50Hz powerline of 1063 pT/√Hz (31 dB).

Outlook:
Residual fields in the MSR remain too high for OPM operation. We are developing active shielding and signal processing techniques to reduce the field, including asymmetric electromagnetic coil designs (to account for MuMetal interactions and off-centre patient head position) and FPGA-driven active compensation at DC and AC. We will also present OPM-MEG data acquired with controlled noise generated by coils inside a 5-layer MSR to simulate conditions in a lightly shielded MSR. This data shows that spatiotemporal signal space separation 2 combined with improved calibration 3, [4] can reduce noise levels from c.5 pT/√Hz to c.100fT/√Hz. These results suggest that, with active shielding to address the powerline, OPM-MEG in a single-layer MSR is achievable.

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Poster Session and Buffet / 52

Towards an Optical Magnetic Gradiometer Using Laser-Written Vapor Cells

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We present a compact optical magnetic gradiometer based on laser-written vapor cells (LWVCs) with a dual-chamber design, aimed at high-sensitivity detection of magnetic field gradients. This system is built around an optically pumped magnetometer (OPM), which enables precise measurements of magnetic variations while rejecting common-mode noise—an essential feature for operation in unshielded environments.

The vapor cells are fabricated using the FLICE method (Femtosecond Laser Irradiation followed by Chemical Etching), which allows for full 3D control of the internal microstructure. This technique makes it possible to create highly compact and integrable vapor cells with carefully designed geometries. In our design, each sensing chamber is 3 mm long and 1.5 mm wide, connected via microchannels that allow controlled vapor flow.

To evaluate the system, we begin with a single-channel configuration to measure absolute magnetic sensitivity and then transition to a dual-chamber setup for gradient field detection. The measurement relies on detecting the Free Induction Decay (FID) signal—an oscillatory, time-dependent response of the atomic ensemble after optical pumping. By analyzing the FID signal from each chamber, we extract the local magnetic field and compute their difference to determine the gradient. Two readout schemes are employed: one based on optical rotation and another using phase shift detection in a Mach-Zehnder interferometer configuration.

With its high spatial resolution, integrability, and sensitivity, this gradiometer is a promising step toward miniaturized quantum sensors suitable for applications ranging from biomedical diagnostics to environmental monitoring.

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Frequency-Domain Blind Source Separation of Biomagnetic Signals Measured with an OPM Array

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Optically pumped magnetometers (OPMs) are highly sensitive sensors that can detect minute biomagnetic fields. However, OPM signals are often degraded by ambient magnetic interference and motion artifacts. To address such noisy signals, we apply independent low-rank matrix analysis (ILRMA), a multichannel blind source separation (BSS) method that leverages the low-rank structure of source power spectrograms in the time-frequency domain. Periodic biomagnetic signals, such as cardiac signals, exhibit clear harmonic structures in their power spectrograms (Figs. (a) and (b)), which can be approximated as low-rank matrices. By exploiting the time-frequency and spatial characteristics of sources, ILRMA effectively separates target physiological signals from noisy multichannel OPM signals.

We conducted a magnetocardiography experiment in a magnetically shielded room using an array of four SERF-type OPMs manufactured by Hamamatsu Photonics K.K. To suppress noise from commercial power sources, the signals were filtered with a 0.5–50 Hz band-pass filter. ILRMA was compared to conventional time-domain independent component analysis (ICA) under determined conditions (equal number of sources and channels). With ICA, cardiac QRS complex patterns appeared across multiple estimated sources (two of four shown in Fig. (c)). In contrast, ILRMA successfully separated the cardiac QRS complex signal from periodic noise as distinct sources (Fig. (d)), demonstrating its superior performance for multichannel magnetocardiography with OPMs.

Figure 13: (a)MCG signal (b)Log-frequency spectrogram (c)ICA separated signals (d)ILRMA separated signals

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Poster Session and Buffet / 54

Improvement of Time Resolution in Scalar Optically Pumped Magnetometers Using State-Space Model

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In conventional magnetic field estimation using scalar-mode optically pumped magnetometers (OPMs), the goal is to estimate the frequency of a decaying sine curve that best fits a free induction decay (FID) signal. This approach assumes a constant magnetic field during each FID period, limiting its ability to track the temporal dynamics of fields oscillating at high frequencies.

To overcome this limitation, we propose a statistical magnetic field estimation method using a physics-informed state-space model (Fig. 1). The state equation, governing the temporal evolution of magnetic fields and spins (latent variables), is derived from a temporally discretized Bloch equation. The observation equation, representing the FID signal (observed variable), is based on the magneto-optical effect, assuming the probe beam is applied along the x-axis. Using an extended Kalman filter and Rauch-Tung-Striebel smoother, the time-varying magnetic field can be estimated from an FID signal at its sampling rate.

We conducted a simulation experiment with time-varying magnetic fields oscillating at 10 Hz (600 pT amplitude) and 10 kHz (1 nT amplitude). The proposed method was compared to the conventional fitting approach. Results showed that the proposed method successfully tracked the 10 kHz field's temporal evolution. For the 10 Hz field, although the proposed method was less accurate than the conventional method, it still captured the slow dynamics. To enhance performance, we plan to reduce noise in FID signals using a differential OPM array.

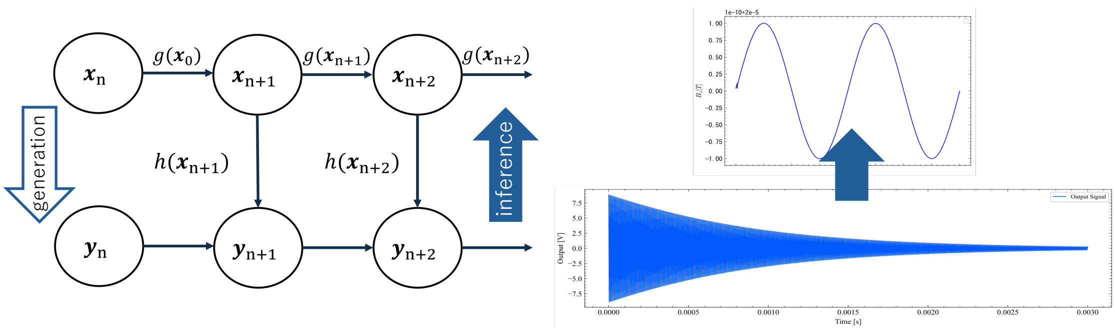

Figure 14: The proposed method based on a state-space model

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High-Density OPM-MEG

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Optically pumped magnetometers (OPMs) present an alternative sensor technology for magnetoencephalography (MEG) to cryogenic systems, allowing for flexible, wearable arrays with reduced sensor-to-scalp distances 1. However, despite rapid progress, current systems have fewer measurement channels (<200) compared to the ˜300 used in cryogenic systems. The potential increase in measured signal and signal-to-noise ratio (SNR) is well documented [2,3,4], but the reduced sensor-to-scalp distances also provide the ability to measure more focal field topographies, ostensibly improving spatial resolution 3. High-Density (HD) OPM-MEG fundamentally requires sensors to be placed in close proximity to one another. This can introduce crosstalk effects (constructive interference of fields from adjacent sensors) which alter the sensitive axes of the sensors. Here we demonstrate findings from a high-density, high channel count OPM-MEG array, utilising calibration methods, quantifying crosstalk effects, and demonstrating improvements in SNR and spatial resolution.

Recent work [5,6] has demonstrated a calibration procedure using a matrix coil (MC) magnetic field nulling system [7] through generation of well-characterised magnetic fields over the OPM sensor array. We have recently refined this procedure, reducing acquisition time from ˜20 s to ˜1 s and improving run-to-run repeatability, reducing the variation in localisation error from ˜1.5 mm per axis to ˜0.4 mm per axis. From this calibration, the true sensitive axes can be determined (including effects from manufacturing tolerances, ambient environment, and crosstalk interference).

A pilot HD-OPM-MEG study assessed induced responses from a ballistic finger abduction paradigm (2s movement, 4s rest, 50 trials for each finger) in a 192-channel OPM-MEG system in which triaxial sensors (QuSpin, Colorado, USA) controlled by integrated miniaturised electronics [8] and mounted in bespoke high-density helmets (Cerca Magnetics, Nottingham, UK). Our initial results suggest that spatial resolution follows a quadratic relationship with sensor density.

We have also built a 384-channel OPM-MEG with 128 triaxial OPMs. We validated the system performance using a phantom containing 5 magnetic dipoles (Cerca Magnetics Ltd), reconstructing the relative locations of the dipoles to one another with sub-mm accuracy. Future work will use this system, in combination with improved calibration techniques and improved co-registration techniques, to further explore the relationship between spatial resolution with increased channel count and identify the effects of different array designs by using subsets of channels in analysis.

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Gamma-band responses in early visual cortices to natural images: broadband gamma is not really broadband

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Narrowband gamma oscillations in the primary visual cortex (V1) have been shown to depend on spatial features and colour in visual stimuli of gratings and uniformly coloured patches [1,2]. In invasive studies, natural images and movies have also been shown to induce these oscillations [1,3]. In non-invasive studies, in contrast, the responses to natural stimuli have been reported to be broadband instead of narrowband [2,4]. Due to its high spatial resolution, OPM-MEG is well-suited for the non-invasive study of weak and focal gamma-band activity 2. We presented 20 healthy human subjects static images of gratings, uniform colours and natural scenes. We measured their responses inside a three-layer MSR with our OPM-MEG system that includes 15 scalp-normal single-axis OPMs (Gen-1/2 QZFM; QuSpin Inc.). We observed gamma-band oscillations in V1 in all subjects, where the power, frequency, temporal dynamics and burst rate of the oscillations were stimulus dependent. Importantly, we found that the broadband gamma response in averaged MEG data consists of narrowband bursts with peak frequencies spanning over the gamma band. These oscillations could be associated with different image features, while potentially being crucial for non-invasive study of gamma-band responses to natural stimuli.

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Developing Adaptive Multipole Models for interference suppression in OPM recordings of spinal cord neurography

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A key motivator for the adoption of OPMs for neural recordings is that they allow recordings from multiple different electrophysiological sources simultaneously. Simultaneous recording from the brain (MEG) and spinal cord (MSG) has recently garnered interest [1,2], as it has the potential to facilitate research into cortico-spinal connectivity, furthering our understanding of sensorimotor processing and recovery following spinal cord injury. However, interference suppression must be carefully considered to advance this novel recording modality. Sources of physiological interference are larger in MSG than MEG, due to the close proximity of back muscles and the heart 3. Additionally, the differing geometry of the torso by comparison to the head means that methods developed for OPM-MEG may not be appropriate for OPM-MSG. In this study, we evaluate the validity of Adaptive Multipole Modelling (AMM) [4] –a post-acquisition interference suppression method for OPM-MEG –for OPM-MSG and suggest an extension to improve its suitability for spinal cord recordings.

AMM is a spatial modelling technique based on spheroidal harmonic models of the magnetic scalar potential. It has been shown to be highly successful for suppressing interference in OPM-MEG recordings. We will show in simulation that, due to the geometry of the torso, spheroidal harmonic functions arising from a single origin point provide a poor description of expected spinal cord signals. We show that extending the internal model to include multiple spheroid locations improves this performance, increasing the minimum correlation between the original and modelled simulated signals (simulated from a 1-shell boundary element model of the torso [5]) from 0.51 to 0.83 for a 9th order model, reflected in a decrease of the Bayesian Information Criterion (BIC) from -3.14e4 to -3.37e4. We consider the impact of different model parameters, including the shape of the reference spheroids used to generate the model basis functions and the model complexity. We then empirically validate performance with median nerve stimulation recordings and quantify the change in SNR of the spinal response after multi-spheroid AMM.

In summary, we show that with a relatively small adaptation, AMM can be effective for interference suppression for neuromagnetic recordings from the spinal cord in simulation and empirically. This increases the feasibility of OPM-MSG recordings, opening up new research avenues into connectivity across the central nervous system.

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Scalar-Mode OPMs with Spin-Echo Technique

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The precision of magnetic field estimation using a scalar-mode optically pumped magnetometer (OPM) is significantly degraded in the presence of environmental magnetic noise. Spatial inhomogeneity in the noise magnetic field reduces the transverse relaxation time, resulting in a shorter, noisier free induction decay (FID) signal. To address this issue, we employ a spin echo technique using a refocusing π radio frequency (RF) pulse. This π pulse inverts dephased spins, compensating for the spatial inhomogeneity of the noise field, as illustrated in Fig. 1. Unlike conventional methods, where FID signals decay rapidly in highly inhomogeneous fields, the proposed method extends the observable signal duration.
We conducted an experiment with a scalar-mode OPM in an open-door magnetic shield. The resonance frequency of the bias magnetic field was set to approximately 15 kHz, and the gradient magnetic field of the spatially inhomogeneous noise field was approximately 3 μT/m. As shown in Fig. 2, a $\frac{\pi}{2}$ pulse was applied at 0 seconds, followed by a π pulse at approximately 1.5 ms. While the FID signal decayed with a time constant of 0.9 ms, the spin echo signal exhibited a longer time constant of 3.0 ms, indicating an extended observation window.
We experimentally confirmed that spin echo signals can be observed even in the presence of spatially inhomogeneous environmental magnetic fields. Future work will investigate the effectiveness of the spin echo technique outside the magnetic shield.

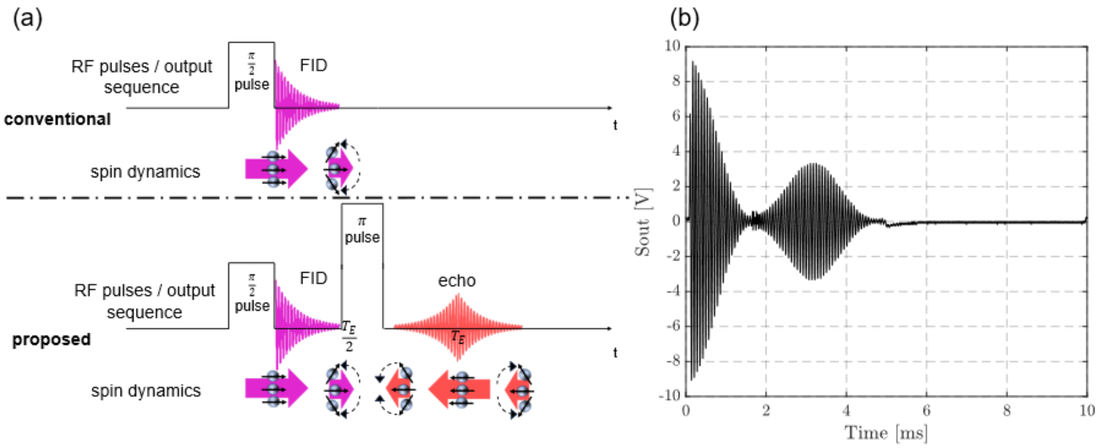

Figure 15: (a) Concept of proposed method (b) Experimental result

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Towards optical quantum control of nuclear spins in a Helium-3 gas

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The nuclear spin of Helium-3 atoms in a room-temperature gas is a very well isolated quantum system featuring record-long coherence times of up to several days. It is used in a variety of applications ranging from magnetometry and gyroscopes to magnetic resonance imaging and precision tests of fundamental physics. While the exceptional isolation of Helium-3 nuclear spins ensures long coherence times, it renders measurement and control difficult. We report first experiments towards optical quantum control of Helium-3 nuclear spins. We make use of metastability-exchange collisions to mediate an effective interaction between the nuclear spins and light, which allows us to read out the coherent nuclear spin dynamics with an optical Faraday measurement 1. Reaching quantum-noise limited detection and increasing the coupling strength will allow us to prepare non-classical nuclear spin states via QND measurements, as we have investigated in a detailed theoretical study [1,2].

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Searching for dark matter with comagnetometers

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Self-compensated comagnetometers, employing overlapping samples of spin-polarized alkali and noble gases are promising sensors for exotic beyond-the-standard-model fields and high-precision metrology such as rotation sensing.

We use comagnetometers to perform an Axion-like particle (ALP) dark matter search. We search through the ALP-nucleon interaction by interfering the signals of two atomic K-Rb-^{3}He comagnetometers, with one situated in Mainz, Germany, and the other in Kraków, Poland. ALPs arise from well-motivated extensions to the Standard Model and could account for dark matter. ALP dark matter would manifest as a nearly monochromatic field oscillating at an as of yet unknown frequency. The frequency depends on the ALP mass, which could plausibly range from 10^{-22} eV/c^2 to 10 eV/c^2. The search extends over nine orders of magnitude in ALP mass. In this range, no significant evidence of an ALP signal is found. We thus place new upper limits on the ALP-neutron, ALP-proton and ALP-electron couplings reaching below $g_{aNN} < 10^{-9}$ GeV^{-1}, $g_{aPP} < 10^{-7}$ GeV^{-1} and $g_{aee} < 10^{-6}$ GeV^{-1}, respectively. These limits improve upon previous laboratory constraints for neutron and proton couplings by up to three orders of magnitude.

Moreover, I will discuss the role of parametric modulation of the leading field to reduce the noise in such quantum sensors.

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Dual isotope spin squeezing in natural mercury hot vapor for quantum enhanced magnetometry

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We investigate the use of optically-addressable nuclear spins in the fermionic isotopes of Mercury (Hg199 and Hg201) for generating macroscopically entangled spin squeezed states [1,2] in hot atomic vapors. We calculate the Wineland spin squeezing parameter 3 under the influence of different atomic loss and spin decoherence sources as well as inhomogeneous atom-light coupling within the Gaussian approximation [4] of atomic spin-f states. The novel aspects about our work are 1) investigating the simultaneous spin squeezing of two optically-addressable nuclear spins (Hg199 and Hg201) in an atomic ensemble of natural-abundance mercury, and 2) demonstrating the metrological advantage of the dual-isotope spin squeezed state in the context of quantum-enhanced magnetometry [6] and discussing possible experimental realizations.

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Synthesized high-density magnetomyography in vivo

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Magnetomyography (MMG), the measurement of magnetic fields produced by muscle activity, remains a scarcely explored topic in biomagnetism. The commercialization of miniaturized zero-field optically pumped magnetometers (OPMs) in the past decade has sparked new interest in in vivo MMG investigations, as sensor grid geometries can now be flexibly adapted to the anatomical shapes of individual muscles. Still, high-density experimental mapping of the spatio-temporal evolution of the magnetic field from in vivo muscles is lacking, greatly complicating both the physiological interpretation of obtained data and the general specification of MMG sensor requirements. In this study, we expand on the method in 1 by employing triaxial zero-field OPMs (QuSpin QZFM, Gen. 3) in a translational grid and performing sequential measurements of the magnetic field from the electrically stimulated abductor digiti minimi (ADM) muscle of the hand. A synthesized 1-mm-pitch magnetic field map is obtained and is set in geometrical relation to the ADM's anatomy through magnetic resonance imaging and 3D scans. The results show both major differences and similarities to simultaneous high-density electromyography recordings and in silico modeling.

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Towards a RF Quantum Sensor based on Rydberg atoms in micro-fabricated vapor cells

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We present the development of a compact and space compatible quantum wideband sensor for radio-frequency (RF) electric fields based on Rydberg atoms in thermal alkali vapor cells.

Rydberg-atom based sensors provide sensitivity to the electric component of RF fields thanks to the high polarizability of excited states.
Unlike traditional RF antennas, these sensors are self-calibrated via atomic constants, miniaturizable below the operating wavelength, and tunable over a wide frequency range (~100 MHz to ~1 THz). These features make them ideal for applications in space situational awareness (SSA), RF imaging, passive radar, communication systems, and quantum metrology.
A Rydberg-based RF sensor operates via a four-level atomic scheme, where a probe laser excites the first transition. RF field detection is based on changes in the probe's optical transmission, resulting from the formation of electromagnetically induced transparency (EIT) via a coupling laser, and Autler–Townes (AT) splitting of the EIT peak, proportional to the target RF field

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Long term stability of an EIT based magnetometer.

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Magnetometers based on Electromagnetically Induced Transparency (EIT) have shown the capability of vector and scalar measurements of magnetic fields in an all-optical interrogation scheme [1, 2]. The magnetic field strength is derived from a relative frequency shift of the atomic resonances proportional to its magnitude, with a scaling factor that depends only on fundamental constants of nature. The orientation of the field can be determined with respect to a fundamentally orthogonal reference frame defined by the wave vector and polarization of the optical field. This intrinsically accurate and stable magnetometer has recently gain attention due to its adaptability to compact systems based on microfabricated atomic cells 3, making it of particular interest in applications where long term and autonomous measurements are required as it eliminates the need of external calibrations. However, the optical detection can degrade the fundamental magnetometer's performance over long integration times due to the effect of the light shift. In this talk we will explain the basic operational principle of the vector CPT magnetometer and present a novel technique that addresses the light shift problem by using linearly polarized light. Among the scalar, vector and tensor components of the light shift, the vector part has a direct impact on the magnetometer performance as it effectively behaves as an additional magnetic field [4]. The linear polarization suppresses this component, so that just the scalar and tensor parts are present [5]. A further cancellation of the remaining drift is obtained using a multi-frequency interrogation technique, called frequency hopping. The reported results provide a promising path toward a highly stable chip-scale vector magnetometer.

*The work was done in collaboration with The College of William & Mary and JPL, and the authors would like to acknowledge the useful inputs from Irina Novikova, Eugeniy E. Mikhailov, James A. McKelvy and Andrey Matsko.

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Generating Realistic Anatomical Templates for OPM Magnetospinography using Conditional 3D Deep Learning

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Recording neuromagnetic fields from the spinal cord with Optically Pumped Magnetometers (OPMs) has the potential to offer new insights into spinal cord function. To realise the full potential of OPM based magnetospinography (OPM-MSG), accurate forward models incorporating subject-specific anatomy are required 1. These models depend on torso and internal organ geometry (heart, lungs, etc.) but acquiring MR images for each participant is resource-intensive. This hinders large-scale adoption of OPM-MSG.

To investigate whether a template anatomy could be used instead, we propose a deep learning approach to generate individual organ structure from a person's torso shape. From the TotalSegmentor CT dataset 2, 3, we obtained segmented meshes of the torso and multiple internal tissue types, including the heart, lungs and bones, from 500 participants. We split this randomly into a training set of 440 participants and a test set of 60 participants using 5-fold cross-validation. To enable convolutional network processing, input torsos and organs were converted into fixed-resolution volumetric grids (e.g., 192x192x192 voxels). A conditional 3D U-Net [4], [5] was trained on these pairs, taking the torso voxel grid as input and learning a complex spatial mapping to predict the 3D shape, location, and inter-relation of the internal organs.

To evaluate this template for OPM-MSG, we plan to test two different anatomical templates in simulation. Using the held-out test data from the TotalSegmentor Dataset, we will simulate OPM-MSG data generated from the participants'own anatomy 1 and reconstruct the source of the simulated data under three conditions: using the participants'own anatomy, using an existing template warped to the participants'torso surface and finally using a template generated from the participants'outer torso surface through a deep learning approach. By considering the distance between the simulated and reconstructed MSG sources in these three conditions, we can begin to answer whether a template could reasonably be used for the spinal cord anatomy in an empirical OPM-MSG recording.

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Characterization of Mercury Vapor Cells for Nuclear Spin-Based OPMs Operating at High Atomic Densities

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Nuclear spin-based OPMs offer a path toward advancing sensitive magnetometry by leveraging the long coherence times of nuclear spin ensembles. Mercury (Hg), particularly its odd isotopes, is a promising candidate due to its accessible 254 nm $^1S_0 \rightarrow \ ^3P_1$ optical transition and high vapor pressure—over 10^3 times that of cesium at room temperature—enabling large optical depths and nuclear spin optical pumping and readout. These properties can compensate for the inherently weaker nuclear magnetic moment, making Hg-based OPMs competitive with electron-spin-based devices. However, prior research [1,2,3] has focused on fundamental physics using cm-scale cells and sub-vapor-pressure densities at room temperature. The regimes of heated Hg vapor cells to reach high atomic densities and sub-mm^3 volumes, critical for sensitive magnetometry and microscopy applications, remain largely unexplored. This high density regime is also promising for quantum-enhanced protocols, where preparing spin-squeezed states via quantum non-demolition (QND) measurements relies on achieving high optical depths.

This work aims to identify favorable combinations of cell parameters that support long spin coherence times at high atomic densities by characterizing a diverse set of natural Hg vapor cells, varying in carbon monoxide (CO) buffer gas pressure, anti-relaxation coatings (bare glass, paraffin, and OTS), and mercury source (HgO vs. metallic Hg), using a 254 nm laser system. The outcomes will guide future designs of compact, high-sensitivity OPMs based on Hg vapor.

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MEG / 67

Evaluating noise suppression algorithms for whole-head OPM-MEG

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OPMs bring new opportunities to MEG but also come with new challenges. With increasing spread and sufficiently large systems becoming available, interference suppression becomes an important subject for many labs doing OPM-MEG. Traditionally used algorithms for interference suppression like signal space separation (SSS) do not work well for OPM-MEG 1. Several promising alternatives have been proposed. Here we aim to evaluate and compare some of the most promising, namely: homogenous field correction (HFC) 2, signal space projection (SSP) 3, iterative applied SSS 1, and adaptive multipole models (AMM) [4].
We simulated data with different types of interference using realistic forward models and sensor noise and extracted shielding factors for the different interference sources, as well as, suppression of brain signals, to compare between algorithms. Finally, tested the algorithms on real data recorded with a whole-head HEDSCAN OPM-MEG system to demonstrate their effectiveness.
We found that different algorithms are suited for different environments and types of interference. HFC achieved high suppression for all interference sources, especially at higher orders, but exhibits a strong trade-off between shielding factor and brain signal suppression when increasing the order. SSP proved powerful for stationary environmental signals and preserves brain signals well. Basic SSS proved instable but with iterative implementation showed good suppression of distant sources. Temporal AMM was best at dealing with "dental wire"interference. Our results can help guide other MEG researchers to find the best methods for their data.

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Poster Session and Buffet / 68

Open-source electronics for magnetically-pulsed free-spin-precession OPMs

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Operating optically pumped magnetometers (OPMs) in unshielded environments is challenging. The sensors need a high dynamic range of at least several 100 nT to not be saturated by environmental noise (e.g. Mains noise), and a bandwidth of at least 1 kHz in order to avoid aliasing effects. Further, a multichannel system is often desired to allow for model-based spatial noise removal. We aim in developing open-source electronics to allow for low-cost multichannel OPM systems. A magnetically-pulsed free-spin-precession (FSP) magnetometer is well suited for unshielded operation. Compared to Mx-OPMs, FSP-OPMs operate without lock-in-amplifiers, avoiding phase-shift problems. While pulse-train-operated optically-pulsed systems are magnetically silent and show promising sensitivities in well-controlled environments, their sensitivity strongly degrades if the temporal magnetic field gradient is high with respect to the sample rate. This is found e.g. during the first instants of the relaxation in magnetorelaxometry of magnetic nanoparticles or in situations with high frequency noise contributions. In such cases, magnetic pulsing can be favorable.

Our OPM head consists of a microfabricated Cs cell with Indium-Tin-Oxide (ITO) heaters (Leibniz IPHT Jena), a 895 nm, 0.2 mW VCSEL Diode (L895VH1, Thorlabs), a lens, linear polarizing sheet, a quarter-wave plate, a photodiode, and a prepolarization coil. Our electronics is composed of a low-noise 3 mA constant-current driver with a 7-bit digital setpoint, pulsed coil drivers for driving the prepolarization coils, the ITO heater and the laser heater. Further it consists of a multi channel PT100 and PT1000 readout electronics for measuring the cell and laser temperature, a transimpedance amplifier with 300 kHz bandwidth, and ADC board with 24-Bit resolution and 1 MSPS.

The laser driver has a current noise of approx. 50 pA/rtHz, while the transimpedance amplifier has a noise floor of approx. 30 pA/rtHz.

Quantum and Fundamental / 69

3He Magnetometry for the Fermilab Muon g-2 experiment

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The Fermilab Muon g-2 Experiment measures the precession frequency of the muon spin relative to its momentum in a 50m circumference storage ring with a 1.45T vertical field and quadrupole electric fields. The magnetic-moment anomaly $a_\mu = (g_\mu - 2)/2$ is determined from this anomalous precession frequency and precision determination of the magnetic field over space and time using a combination of proton-NMR magnetometers. The calibration chain for these magnetometers includes optically-pumped ^{3}He magnetometry based on metastability-exchange optical pumping (MEOP). Corrections to a "perfect" magnetometer that would accurately measure the magnetic field at a specific position are determined to less than 14 ppb in the 1.45 T field. The application to calibration of the muon g-2 proton-NMR magnetometer array and other applications will be discussed. Prospects for improved measurement of the diamagnetic shielding of protons in H_2O will also be presented.

Poster Session and Buffet / 70

A detection system for magnetic contamination in n2EDM

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The n2EDM experiment at the Paul Scherrer Institut aims to probe the neutron electric dipole moment with a sensitivity below 10^{-27} $e{\cdot}\mathrm{cm}$, requiring an exceptionally clean magnetic environment. To identify minuscule magnetic impurities that could introduce false EDM signals, we developed a mobile gradiometer based on optically pumped cesium magnetometers in the Mx configuration. The system detects dipole moments down to 0.1 nAm^2, using differential phase-sensitive readout to map magnetic gradients with sub-picotesla sensitivity. The device leverages the high precision and robustness of cesium magnetometry to scan materials under realistic experimental conditions, providing essential diagnostics for maintaining magnetic integrity in the n2EDM apparatus.

Authors: Luz Sanchez-Real Zielniewicz, Lea Segner, Judith van Keirsbilck, Victoria Kletzl, Georg Bison, Vira Bondar on behalf of the nEDM collaboration

Acknowledgement of grants: Swiss National Science Foundation 200441, 213222 and 236419.

Poster Session and Buffet / 71

Development of a Spin-Squeezed Scalar OPM in Pursuit of Practical Entanglement Advantage

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Optically pumped magnetometers (OPMs) utilizing entangled spins offer the promise of sensing performance beyond the standard quantum limit (SQL). Unfortunately, realizing this advantage has proven exceedingly difficult. Entangled states are inherently tricky to create and maintain. It is often better to simply use many unentangled atoms rather than entangling far fewer of them. Nevertheless, recent work by the Polzik group has shown promising progress in the generation and utilization of spin-squeezed states in pulsed radiofrequency OPMs that can surpass the SQL (1).

Inspired by this approach, we are developing a scalar OPM that utilizes a similar pulsed interrogation methodology. The key is a stroboscopic interrogation sequence that is pulsed at twice the Larmor frequency to implement a quantum nondemolition (QND) measurement of the spins. To implement squeezing, this method is used to measure the spins both before and after a free evolution period in which the spins interact with external magnetic fields. Conditioning the final uncertainty in magnetic field on information obtained via the pre-interaction measurement can reduce the final uncertainty below the SQL; the spin ensemble has been put into a squeezed state through a process known as conditional squeezing.

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This project has two aims: development of a strong theoretical model to explore the underlaying dynamics of the hot vapor cell on which the OPM is based so we may best predict and optimize squeezing performance and building an experimental platform to test these predictions. Based on the foundation laid by the Romalis group(2) , we are working to implement multiple passings of the probe beam through the vapor cell via a collaboration with Opto-Assembly Inc. Such a multi-passed design leads to a much greater effective optical depth experienced by the probe beam, which can greatly improve the SNR of detection that relies on optical Faraday rotation. This reduces the magnetic field uncertainty stemming from photon shot noise in comparison to the spin-projection noise. Since spin-squeezing can improve only the latter, this architecture should help us realize greater benefits from spin-squeezing.

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OPM Development I / 72

A Sensitive Dead-Zone-Free FID Magnetometer

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Detection dead-zones are important systematic effects in scalar atomic magnetometers, which limit their practical applications. In this work, we demonstrate a sensitive dead-zone-free scalar magnetometer by applying previously developed techniques in a FID magnetometer [1,2]. The detection dead zones are eliminated by adding a reflecting mirror in the middle of a multipass-cavity-assisted cell which bends beam paths inside the cell. Preliminary measurement results show that the change of SNR is two times worse than theoretical estimation, which predicts that sensor signal-to-noise ratio (SNR) is limited within in 50% over sensor orientations in the three dimensional space. However, this still leads to a field sensitivity better than 150 fT/Hz1/2 for any sensor orientation. This work paves the way for a vector FID magnetometer. In this talk, we will present detailed measurement results and the development of a vector magnetometer based on such a sensor.

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Poster Session and Buffet / 73

Laser cleaning optical windows of alkali vapor cells

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Alkali vapor cells are at the heart of a variety of atomic systems and quantum sensors, including atomic clocks and gyroscopes, laser frequency references, Rydberg atom-based electric field sensors, and especially for this work, optically pumped magnetometers. In state-of-the-art, wafer-scale vapor cell fabrication technology, the alkali metal is often introduced as a chemical compound into the cells 1. The elemental alkali metal is subsequently released inside the sealed cells by additional steps, for example using photolysis [2,3] or other chemical reactions [4,5]. In these approaches, unwanted substances typically remain inside the cells, e.g., residues of reactants or reaction byproducts. When these contaminations remain at the optical windows of the cells, they can degrade the performance of the cells and limit the reproducibility of their (optical) properties.

In this work, we present a method for cleaning the optical windows of alkali vapor cells based on femtosecond laser ablation. We demonstrate removal of the residues released from an alkali metal dispenser pill and remains of cesium azide from the optical windows of microfabricated Cs cells. We evaluate the efficiency of the laser cleaning process by comparing the optical transmission of a cleaned area with that of a still-contaminated region of the same cell. In addition to that, the spectra of the cells before and after the treatment have been compared with respect to a possible change of the background pressure of the buffer gas.

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Poster Session and Buffet / 74

Functionalized mm-scale Vapor Cells for high sensitivity optically pumped magnetometers (OPMs)

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Miniaturized high-sensitivity OPMs require –simultaneously –small volumes, temperature control, magnetic field control, and low magnetic noise. This presents interlinked challenges when designing vapor cells for OPMs. We report a dual-chamber ($4\times4\times1.5$ mm^3) low-noise functionalized vapor cell (FVC) and its use in a single-beam SERF OPM. The FVC, made at wafer scale by MEMS techniques, incorporates surface metallization for both heating and thermal monitoring, while also maintaining a low thermal magnetic noise. We discuss also the zero-field operation of the OPM, in which we observe a magnetic sensitivity of about $18\mathrm{fT}/\sqrt{\mathrm{Hz}}$. This FVC design is a step toward mass producible OPMs for applications in sectors including medical imaging, space and geophysical.

Poster Session and Buffet / 75

Stimulated abductor digiti minimi muscle measured by SQUID, OPM, and sEMG in magnetically shielded environment

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We report measurements of the bioelectricity of the electrically stimulated abductor digiti minimi (ADM) muscle of the right hand using three types of measurement modalities:
(1) by recording magnetic flux density with a state of the art zero field optically pumped magnetometer (OPM),
(2) by recording magnetic flux density with a superconducting quantum interference device (SQUID), and
(3) by recording the electric potential at the skin with a high-density grid of surface electromyography (sEMG) electrodes.
For the magnetic measurements we recorded the radial field component with OPM and SQUID. Both sensors have a similar size of the sensing element and a distance to the outer shell of about 6 mm, enabling an effective sensor-to-skin distance of about 10 mm in both cases. Despite the limited characteristics in terms of bandwidth and transfer function of the chosen OPM, we observed only slightly distorted, similar signal shapes compared to the stimulated ADM recordings performed with the SQUID. We found that the spectral profile and frequency content differed only slightly in all three measurement modalities. This work provides an initial validation of whether magnetomyography (MMG) using flexible and easy-to-use OPMs can be a useful alternative to surface electromyography (sEMG) in terms of sensor capabilities.

OPM Applications I / 76

Development of a portable double-resonance OPM for use in space weather observation

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Optically Pumped magnetometers (OPMs) have seen recent advances due to the emergence of new interrogation schemes, operational modalities, and availability of improved components forming the sensors. The use of microfabrication techniques for manufacturing alkali vapour cells [1,2], miniature optics and the integration of chip-scale lasers, allows for mass-production of compact, high sensitivity sensors.
These advances transformed laboratory-based OPM experiments into portable devices that can be fielded as practical sensors and used for a myriad of applications, ranging from biomedical, such as magnetocardiography (MCG) and magnetoencephalography [3,4], as well as industrial applications such as navigation [5] or non-destructive testing [6].

We will present a portable double-resonance OPM developed at Strathclyde, offering accurate and precise geomagnetic measurements in a compact package. We will show a practical application of this sensor in a new national network of magnetic observation [7], which can be used to monitor the effects of space weather, including observation of geomagnetic storms [8]. These high-performance practical measurements have been underpinned by in-depth optimisation of MEMS cell design, fabrication, filling, and validation [1,2]. These techniques will also be discussed.

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OPM Applications III / 77

In-Orbit Performance of the Coupled Dark State Magnetometer

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The Coupled Dark State Magnetometer (CDSM) is a magnetometer developed by the Space Research Institute of the Austrian Academy of Sciences in cooperation with the Graz University of Technology. It is a optically pumped scalar magnetometer based on two-photon spectroscopy of free alkali atoms (Rubidium 87).
The CDSM is currently operating on three space missions and will have launched on a fourth on 11 June 2025. The three missions "China Seismo-Electromagnetic Satellite 1"(CSES1; launched in February 2018), "Macau Science Satellite"(MSS1; launched in May 2023) and "China Seismo-Electromagnetic Satellite 2"(CSES2; launched in June 2025) were launched into Low-Earth-Orbit. The "Jupiter Icy Moons Explorer"(JUICE; launched in April 2023) is bound to explore the Ionian moons (arrival 2031) and had an Earth fly-by in August 2025.
After a short introduction to the CDSM, selected mission data is presented with a special emphasis on the MSS1 mission. The performance of the CDSM is evaluated in three ways: First the data is compared to the CHAOS Earth's field model. Secondly, for CSES1 and MSS1 the data is cross-validated with data from ESA's SWARM mission. Last is an internal comparison with fluxgate magnetometer(s) on the same spacecraft.
Based on this analysis, the CDSM demonstrates an accuracy better than 1.5 nT across the entire measurement range of 20,000 nT to 50,000 nT.

OPM Development II / 78

High-resolution magnetic field imaging with a two-axis MEMS scanning mirror

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We demonstrate high-resolution magnetic field imaging using a custom micro-machined cesium (Cs) vapor cell filled with nitrogen (N_2) buffer gas 1, incorporating automated spatial sampling via a two-axis MEMS scanning mirror. The cell utilizes advanced fabrication techniques that enable flexible and scalable geometries, making it well suited for a variety of applications, including magnetic imaging 2. An optically pumped magnetometer (OPM) operating in the free-induction-decay (FID) protocol is employed. Renowned for its high accuracy and stability, this technique is also discussed in the context of portable sensor implementations used to detect space weather phenomena.

By resonantly pumping the Cs D_2 transition, near-unity spin polarization is achieved, maximizing signal amplitude. Spin-exchange effects are suppressed via light narrowing, which reduces the transverse relaxation rate (γ_2). Combined with an advanced optical pumping strategy, this results in sub-picotesla sensitivity across a broad dynamic range, supporting accurate and stable imaging in finite-field environments 3.

Spatial confinement provided by the buffer gas enables locally independent measurements within a single vapor cell. This capability is harnessed to image a variety of magnetic sources using a single-pixel FID-based sensor. Two-dimensional magnetic field images with high spatial and temporal resolution are generated which has significant implications for applications including battery diagnostics and electronic circuit quality assurance.

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Poster Session and Buffet / 79

Magnetometry in maritime conditions

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Until now, highly sensitive optically pumped magnetometers (OPMs) have mainly been used in shielded environments under strictly controlled laboratory conditions. However, for a continuous dissemination of this technology and the development of additional areas of application and research, it will be essential to adapt it to more challenging environments.

In particular, the maritime domain poses a challenge due to harsh environmental conditions, limited accessibility as well as natural and artificial sources of interference. At the same time, the sea is also a scientifically exciting and complex system with many open research questions, for example in the field of magnetohydrodynamics, geology or biology, which could be further investigated with modern sensor technology like OPMs.

The poster presentation will show how the path to a maritime adaptation of magnetic field sensors and optically pumped magnetometers is being paved as part of applied research work at WTD 71 and which particular challenges need to be solved. Examples will be given of how magnetic field sensors can be deployed at sea for scientific experiments, which special conditions need to be considered and how further development could be realized.

Poster Session and Buffet / 80

Magnetic flux density measurements using MEOP hyperpolarized ^{3}He in low fields

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The current method for disseminating the unit Tesla relies on NMR measurements on field polarized proton spins, using water 1. However, the relative measurement uncertainties are restricted to values between 10^{-4} and 10^{-6} by limited SNR at fields below 2 mT and a rather insensitive absorption technique at fields above 10 mT. To overcome these limitations, we explore the use of hyperpolarized ^{3}He gas, which offers field independent enhanced SNR in combination with longer precession times T_2^* 2, thereby promising higher precision over a very wide magnetic field range. Using metastability exchange optical pumping (MEOP) to achieve hyperpolarization 3 promises fast buildup times and avoids interaction of the polarized alkali atoms on ^{3}He precession and the application of complicated pulse sequences for sufficient decoupling thereof[4].

Our experimental setup ^{3}He MEOP magnetometry includes a commercial table-top four-layer magnetic shield with integrated coils, enabling the generation of a constant B_0 field in the µT-range alongside a perpendicular, resonant B_1 field to initiate spin precession. Utilizing a commercial Rubidium (Rb) optical pumped magnetic gradiometer (OMG) with a 2.3 cm baseline, we have measured the ^3He magnetization precession, allowing us to deduce the Larmor frequency at varying B_0 magnetic field strengths. With the setup we determine polarization buildup times and T_2^* relaxation times. By varying the flip angle, we show systematic effects of residual longitudinal magnetization in the ^{3}He on the detected Larmor frequency. This allows conclusions to be drawn about the imperfect sphericity of the cell geometry.

To validate the precision of our setup, experiments are planned within a large magnetically shielded room, which offers a more stable magnetic field and enables the measurement with superconducting quantum interference devices (SQUIDs) for the ^{3}He magnetization precession. Using SQUIDS facilitates higher SNR and measurements at lower B_0 fields compared to the Rb gradiometer. These investigations will compare the detectable B_0 field by ^{3}He nuclei using different sensor types—OMG versus SQUID—enhancing our understanding of the influence of sensors on the precision of magnetic field metrology.

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OPM Development II / 81

Fabrication and Application: In-situ monitoring system for anti-relaxation coating atomic vapor cells

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Anti-relaxation coating (ARC) vapor cells are a critical component in atomic physics and quantum sensing, yet their widespread adoption is hindered by short spin coherence times and low manufacturing yields, stemming from the lack of systematic preparation protocols. Herein, we present an in-situ monitoring system that enables real-time optimization of the spin coherence time and vapor density during the ARC vapor cell preparation. By integrating real-time process monitoring and closed-loop feedback control into the empirical cell-curing method, our system dynamically adjusts the curing parameters to optimize the spin coherence time to second-scale. The proposed system improves the manufacturing yield of ARC vapor cells and provides a foundational platform for the advancement of quantum sensors.

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(a) Schematic of the experimental device. (b) The structure of the oven. (c) Characterization indices of vapor cells manufactured with three methods. The T_1 and n of three batches of vapor cells are marked in blue, green and red, which is uncured, empirical cured and in-situ cured, respectively. The black dotted line is the requirement curve, presenting the constant product of T_1 and n, corresponding to limit of δB_{SNL} of femtotesla level.

Poster Session and Buffet / 82

Auditory evoked responses of domestic cats measured using OPM-MEG

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Auditory evoked responses, recorded using electroencephalography or magnetoencephalography (MEG), are commonly used to study cognitive processes related to hearing in humans. These responses have also been recorded in other species but mostly by using invasive techniques. Here, for the first time, we present non-invasive measurements of these responses in unanesthetized domestic cats (Felis catus) using optically pumped magnetometers (OPMs). Our aim is to study the feline-equivalents of the human N100, mismatch negativity and P300 responses to bridge the gap between previous invasive animal and non-invasive human studies. N100 is an automatic response to novel sounds, mismatch negativity a response to deviant tones, and P300 an attention-related response indicating updates of the short-term memory.

We measured eight cats using an array of eight dual-axis OPMs (QZFM Gen-2, QuSpin Inc., Louisville, CO, USA) placed in a custom 3D-printed helmet that conforms to the average shape of a cat's head. We presented the cats a series of tone beeps according to a variation of the local–global paradigm. Each trial comprised a sequence of five 50-ms tones: the first four tones were always the same and the last one was either the same or different in frequency with respect to the preceding ones. Trials were presented in blocks where in 75% of the trials the 5th tone was different and in 25% the same as the preceding four tones. In a block, we used 1-kHz tones as the common sound and 50-kHz ultrasound tones as the deviant ones.

During measurements, the cat was seated with its owner and was free to move its head, while the owner was holding the sensor helmet on the cat's head. The experiment was performed in a three-layer magnetically shielded room.

A putative N100-response equivalent was succesfully measured on average 65 ms after the sound onset. Some evidence for mismatch negativity was observed as a larger-amplitude N100 after deviant tones. Convincing evidence for P300 was not observed. We showed that neurophysiological experiments can be performed non-invasively and without restraining the animals using OPM-based MEG.

Poster Session and Buffet / 83

Magnetometry using Four Wave Mixing of Sodium Vapour

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Four wave mixing is a popular spectroscopic technique with limited examples of use for magnetometry. As an all optical, heterodyne technique, it allows for high sensitivity measurement, without the challenges associated with using RF.

All akali vapours could be used for four wave mixing, however we selected sodium due to having the vapour cell and dye laser readily available in our lab. A high power, linearly polarised pump beam, is mixed with a small left circularly polarised probe beam. When the probe beam is resonant with the magnetic field, a right circularly polarised conjugate beam is generated at an opposite angle to the probe beam.

The conjugate and probe beams are beat together at the photodetector, with the beat frequency twice that of the magnetic field splitting. The estimated sensitivity for four wave mixing with sodium vapour is on the order of 1 pT/Hz^-1/2. This is without magnetic shielding, unlike many conventional OPM experiments.

OPM Applications III / 84

Development of a Zero-Field/Hanle Vector Magnetometer for Exploring Magnetic Fields in Space

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Optically pumped magnetometers have been integral to scientific space applications since the 1960s 1. They not only explore the Earth's magnetic field aboard missions such as Swarm (since 2013) 2 and CSES-1 (since 2018) 3, but also the magnetic fields of other planets and their moons. Notable missions include Pioneer 11 (Jupiter flyby in 1974), Mariner 10 (Mercury flyby in 1974) and Cassini (orbiting Saturn from 2004 to 2017) 1. Currently, an optically pumped scalar magnetometer is on its way to Jupiter aboard the JUICE mission expected to arrive in 2031 [4]. Additionally, several instruments will be launched into Earth orbits soon, such as on CSES-2 (scheduled for 2025) and on NanoMagSat (scheduled for 2027) [5]. Despite all these achievements, the fluxgate magnetometer remains the most widely used magnetometer in space [6]. This type of instrument employs a feedback coil system with a ferromagnetic core for vector measurements [7].
The presentation will provide an overview of the requirements for magnetic field measurements in various mission scenarios, as well as the challenging environmental conditions during launch and the subsequent year-long operation in space. It will consider the advantages of fluxgate magnetometers and optically pumped scalar magnetometers to determine the performance characteristics required for a potential replacement by a single optical vector magnetometer.
Building on the technologies and experience developed for the Coupled Dark State Magnetometer [3,4], the presentation will show the progress of a zero-field/Hanle vector magnetometer prototype, currently being developed with the space application requirements in mind.

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Poster Session and Buffet / 85

Novel approach for the fabrication of all glass based atomic vapor cells

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A novel approach for the fabrication of glass-based atomic vapor cells is presented, combining laser-assisted glass structuring and a hermetic glass joining technique. The structure of these glass-based cells includes three glass chips stacked on top of each other, with the central chip containing interconnected cavities. Glass structuring using selective laser-induced etching (SLE) process affords great design flexibility for the connecting channel structure as well as three-dimensional structuring of the cavities in transparent materials such as quartz glass or borosilicate glass. The length of the optical path through the vapor cell is determined by the thickness of the central chip, which can be adjusted up to 10 mm. This allows the interaction length to be customised based on experimental requirements. The glass chips are sealed under vacuum conditions using an advanced glass joining technique. Alkali atoms are then introduced into the vapor cell via laser activation of an alkali metal dispenser. For the proof of concept, vapor cells with a 1 mm thick central chip were manufactured, as shown in figure 1. In initial measurements, a Rb spectrum (figure 2) of the fabricated cells was successfully recorded using laser spectroscopy, demonstrating both hermetic sealing and successful laser activation of the dispenser pill.

Figure 1:Fabricated glass-based atomic vapor cells

Figure 2:Rb spectrum of the glass-based vapor cell

OPM Applications I / 86

Mobile total field optically pumped magnetometers for navigation

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Global navigation satellite systems (GNSS) are at the forefront of navigation and are ubiquitous in everyday life. However, GNSS has limitations for use cases where satellite reception is limited, such as underground navigation. The upkeep of existing satellite infrastructure, as well as the prevalence of jamming and spoofing devices limit the reliability of GNSS for the localisation of critical hardware. One alternative solution that does not suffer from these drawbacks is magnetic field navigation 1. This technique uses maps of local magnetic field anomalies and map-matching algorithms to determine position.
We present a modular total field optically pumped magnetometer (OPM) system 2 capable of operating within Earth's magnetic field. A common technique for mitigating platform noise is by offsetting the sensor as far away from the platform as possible. In many real world applications this is not feasible and a compact form factor is required and therefore the contributions from platform noise to the overall magnetic measurement must be addressed. We showcase some of our magnetic data and explore the challenges of suppressing platform related magnetic disturbances.

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Poster Session and Buffet / 87

An optically pumped magnetometer array used for a fundamental physics experiment

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The n2EDM experiment at the Paul Scherrer Institute is a fundamental particle physics experiment which aims to measure the neutron electric dipole moment with a sensitivity below $1 \times 10^{-27}\,\mathrm{e}\cdot\mathrm{cm}$. Achieving this level of sensitivity requires exact control of magnetic field uniformity to reduce systematic effects. To this end, an array of 112 optically pumped cesium vapor magnetometers using a free alignment precession measurement principle will be deployed.
This array will provide real-time measurements of magnetic field gradients, enabling the control and reduction of systematic uncertainties arising from magnetic field non-uniformities. In this contribution, the design, performance, and integration of this system into the experimental setup will be presented.

Poster Session and Buffet / 88

Drone Integration of an Atomic Optically Pumped Magnetometer for Airborne Magnetic Field Sensing

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We present early results on the integration of a compact, hot-vapor based optically pumped magnetometer (OPM) onto a drone platform for unshielded airborne magnetic sensing. This work is part of a broader effort to develop quantum magnetometry solutions for field applications for geo-prospection and the detection of unexploded ordnance. The system employs an alkali vapour-based OPM operating at a data rate of 1 kSa/s, offering high temporal resolution suitable for drone-based surveys.
Particular attention has been paid to keeping the sensor lightweight, integrating it with the drone's onboard and navigation systems, and ensuring electromagnetic compatibility between the sensor and drone electronics.
A test campaign is underway to explore the system's ability to capture magnetic field data during flight, providing a platform for evaluating performance and guiding the next development phase toward an airborne gradiometer.
This poster outlines the system design, integration challenges, and initial flight data, setting the stage for the next phases of in-field deployment.

OPM Applications I / 89

Rotation sensing with 14N/15N and 13C nuclear spins in diamond

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Rotation sensing with ^{14}N/^{15}N and ^{13}C nuclear spins in diamond

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Diamonds doped with nitrogen-vacancy (NV) centers are a promising solid-state platform for rotation sensing [1,2] capable of operating in a broad range of environmental conditions. In our previous work 3, we demonstrated a solid-state rotation sensor based on ^{14}N nuclear spins intrinsic to NV centers in diamond. This type of sensor detects rotation by measuring the shift in the precession rate of nuclear spins, analogous to vapor-based NMR devices. However, nuclear-spin-based rotation sensors are inherently sensitive to variations in the magnetic field, which produce changes in the precession rate similar to those produced by rotation, limiting the long-term stability of the device. This issue can be overcome by simultaneously measuring the precession of two spin species with different gyromagnetic ratios, which can be combined to obtain the rotation rate while canceling the contribution from magnetic field fluctuations.

In this work we implement this idea using a diamond containing two isotopes of nitrogen (^{14}N and ^{15}N) and simultaneously measure the precession rates of NV nuclear spins of both isotopes. We found that we were able to suppress the magnetic sensitivity of the rotation sensor by several orders of magnitude. We also investigate the use of ^{13}C nuclear spins in diamond as a candidate system for rotation sensing. We demonstrate a technique that takes advantage of microwave-swept "Landau-Zener"crossover resonances to transfer spin polarization between NV electron spins and 13C nuclear spins via their transverse hyperfine interaction [4,5], allowing for both optical hyperpolarization and readout.

The nuclear spin interferometric technique developed in this work may find application in solid-state frequency references and in extending tests of fundamental interactions at micro- and nanoscale to those involving nuclear spins. With further improvements, it may also find use in practical devices such as miniature diamond gyroscopes for navigational applications.

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OPM Applications III / 90

Fluid flow monitoring using optically pumped magnetometers

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Monitoring blood circulation, known as hemodynamic monitoring, is vital for assessing patient health. However, obtaining detailed blood flow information non-invasively remains a challenge. To address this, we developed a system that uses strong permanent magnets and optically pumped magnetometers to detect the flow of a pulsed liquid. Our setup enables us to track polarised water moving through a tube and determine its flow velocity. The measured values align well with predictions based on polarisation and magnetisation decay models. These early results demonstrate the potential of this method for future blood flow studies.

Poster Session and Buffet / 91

Hearing threshold assessment with OPM Neuro-1 system

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Auditory Brainstem Response (ABR) testing is currently the only clinical method for objectively determining hearing thresholds by detecting wave V of Auditory Evoked Potentials (AEPs). Its magnetic counterpart, Auditory Evoked Fields (AEFs), offers a promising alternative by identifying the sound pressure level (SPL) at which auditory responses, such as the M100, are detectable.

Whilst traditional SQUID-based magnetoencephalography (MEG) systems were applied in measurements of Auditory Evoked Fields at peri-threshold levels in some studies [1,2,3], maintenance cost and fixed sensor placement limit their use in clinical practice. Here we present results of MEG with Optically Pumped Magnetometers (OPMs), particularly the Neuro-1 integrated sensor system, with its advantages over SQUID systems, enhancing signal amplitude and reducing cost.

To study OPMs utility in assessing hearing threshold at 1 kHz, hearing thresholds of volunteers were first determined using tonal audiometry. Auditory responses to tones 3–10 dB above individual hearing threshold (dB SL, where SL stands for sensational level) were recorded with both SQUID-MEG and Neuro-1 systems in shielded environments.

Auditory M100 responses were reliably detected at 10 dB SL in both systems, with OPM-MEG providing significantly stronger M100 responses due to closer sensor proximity. The study confirms the feasibility of using OPMs for objective hearing threshold estimation and supports their use as a practical, cost-effective alternative to SQUIDs. The ease of use of Neuro-1 integrated sensor system for OPMs and lower maintenance cost is a clear advantage.

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Poster Session and Buffet / 92

In-situ Measurement of Optical Rotation Angle Based on PEM Detection in SERF Magnetometer

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For SERF atomic magnetometer, photo-elastic modulator (PEM) is a commonly-used optical polarimetry technique to detect the weak angle signal due to its high sensitivity. Magnetic field to be measured can be obtained by demodulating the first-harmonic response signal from the photoelectric detector (PD) based on the modulation frequency of PEM. The optical rotation angle contains essential information including atom number density and transverse polarization, thereby accurate measurement of the optical rotation angle is very important. However, in previous studies, the optical rotation angle cannot be derived directly and quantitatively through the demodulated first harmonic signal. Therefore, we propose an in-situ measurement method of the optical rotation angle based on the dc and second harmonic components with PEM detection in SERF atomic magnetometer. We analyze the condition when a modulated linearly-polarized light can be derived by PEM. Further, we establish the expressions of the demodulated response signals by second-order approximation and verify our method by experiments. Our method does not introduce additional device and could be generally used in analysis of polarization and atom number density distribution. Moreover, our method is completely unaffected by the variation of the probe beam intensity and convenient for optical rotation angle measurement under PEM modulation in general optical systems, including but not limited to SERF magnetometer.

$$U = kI_{\text{probe}}\left[\varphi^2 + \frac{1}{2}{\alpha_{\text{m}}}^2 + 2\varphi\alpha_{\text{m}}\sin\left(2\pi ft\right) - \frac{1}{2}{\alpha_{\text{m}}}^2\cos\left(4\pi ft\right)\right]$$
$$\varphi^2 = \frac{U_{\text{dc}} - U_{\text{2nd}}}{2U_{\text{2nd}}}{\alpha_{\text{m}}}^2$$

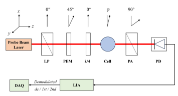

Figure 16: The optical polarimetry measurement based on PEM in the SERF atomic magnetometer.

The optical polarimetry measurement based on PEM in the SERF atomic magnetometer.

Poster Session and Buffet / 93

Three axial automatic compensation system for reducing slow fluctuation inside MSR

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Magnetically shielded rooms (MSRs) significantly attenuate the ambient magnetic field, making it possible to perform measurements of very low signals. For measurements with optically pumped magnetometers (OPMs), such rooms are, in most cases, essential. In a two-layer magnetically shielded room at the Faculty of Mechatronics, Warsaw University of Technology, the QuSpin Zero-Field Magnetometer (QZFM) sensors are in use.

These sensors are equipped with an internal compensation for the static ambient magnetic field, making them suitable for magnetic field measurements within the range down to ±5 nT. However, the urban environment affects the measurement conditions inside the MSR. The proximity of tram and subway lines, with drives powered by direct current, causes slow changes in magnetic induction that are present inside the MSR. Such environmental noise impacts the performance of OPM sensors, especially at the sensitivity of 8.1nT/V, as temporary sensor saturation and data loss may occur.

Here we present a three-axis magnetic field compensation system designed to reduce slow fluctuations of the magnetic field. The system allows for the suppression of low-frequency (below 1 Hz) magnetic field fluctuations within the working area of the compensation coils 1. The control loop is based on fluxgate sensors, which lowers the overall cost of the system. The data from OPM sensors 2 is not required for the compensation system to operate.

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Poster Session and Buffet / 94

Magnetometry with stroboscopic probe light

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Atomic-optical magnetometers have reached sensitivities where quantum noise becomes a limiting factor. One fundamental quantum noise source is back-action noise, which arises from the coupling between quantum fluctuations in the probe light's polarization and the atomic spin ensemble being measured. This back-action can be circumvented by stroboscopically modulating the probe intensity at twice the Larmor frequency, effectively decoupling the light's quantum fluctuations from the observed atomic-spin system 1. Beyond reducing measurement noise, this technique opens the door to generating spin-squeezed states, offering further sensitivity enhancement.
Previous studies have demonstrated the effectiveness of stroboscopic probing under conditions where the second-rank tensor polarizability —a Hamiltonian term associated with atomic alignment effects —is negligible. This regime arises in the presence of buffer gas or when the probe light is detuned far from resonance, rendering the excited-state hyperfine structure unresolved. In contrast, when this tensor contribution is significant, it has been shown to enable both spin and light squeezing, offering additional avenues to enhance magnetometric sensitivity [2, 3]. Notably, these effects have been observed using continuous, unmodulated probe light, and their effectiveness relied on the use of two oppositely oriented spin ensembles.
In this work, we investigate stroboscopic probing of a single ensemble in a regime where the second-rank tensor polarizability cannot be ignored. We observe distinctive features in the spin noise spectrum and explore the conditions under which polarization-squeezed light is generated via the interaction of stroboscopically modulated light with the atomic ensemble. The resulting squeezing, centered near the Larmor frequency, offers a promising path for improving the performance of atomic magnetometers.

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Poster Session and Buffet / 95

Test-retest reliability of auditory MMN measured with OPM-MEG

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Magnetoencephalography (MEG) based on optically pumped magnetometers (OPM-MEG) is a relatively novel method to measure brain activity non-invasively in humans. It offers several advantages over traditional SQUID (superconducting quantum interference device) based MEG and EEG [1-3]. However, its properties, in particular test-retest reliability (stability of measurements in time) and construct validity (agreement of results with established technologies), need to be evaluated to make day-to-day, routine applications possible.

In this quality control study, we investigated the reliability and validity of auditory mismatch negativity (MMN) recordings from a newly installed OPM-MEG system (Cerca Magnetics Limited, Nottingham, UK) utilizing 64 triaxial sensors (QuSpin, Louisville, CO, USA). The auditory MMN is an electrophysiological response to rule violations in auditory input streams [4], which has been interpreted as reflecting the update of a predictive (generative) model of the acoustic environment [5]. We recorded OPM-MEG from 30 healthy volunteers, measured twice within 24-72 hours, using an established auditory MMN paradigm [6]. First, we focused on construct validity and investigated whether OPM-MEG measurements of MMN responses were qualitatively comparable in terms of event-related fields, timing and topography to previous MMN findings of studies using EEG and traditional MEG. Second, we assessed the test-retest reliability (quantified by intra-class correlation coefficients, ICC) of cognitive (MMN) and sensory (auditory M100) evoked fields, comparing the sensor-level response amplitude and latency over the two separate measurement sessions.

The MMN responses recorded with our OPM-MEG setup are in good agreement with previously reported MMN results of EEG and SQUID-based MEG measurements in terms of both timing and topography. For an illustration of the resulted statistical parametric map of the MMN event related radial field, see Figure 1. The qualitative comparison of group-level MMN topographies and timeseries shows excellent consistency across the two measurement sessions. Test-retest reliability analyses indicate moderate reliability for MMN amplitude (ICC=0.50-0.67 for the z-component of the triaxial sensor signal) but poor reliability for latency (ICC=0.00-0.22), in line with previous EEG literature [7]. By contrast, test-retest reliability of the purely sensory M100 auditory evoked fields has been found to be excellent for amplitude (ICC=0.97) and good-to-excellent for latency (ICC=0.84-0.96), confirming the functionality of our setup in the "out-of-the-box" state without further technical optimisation.

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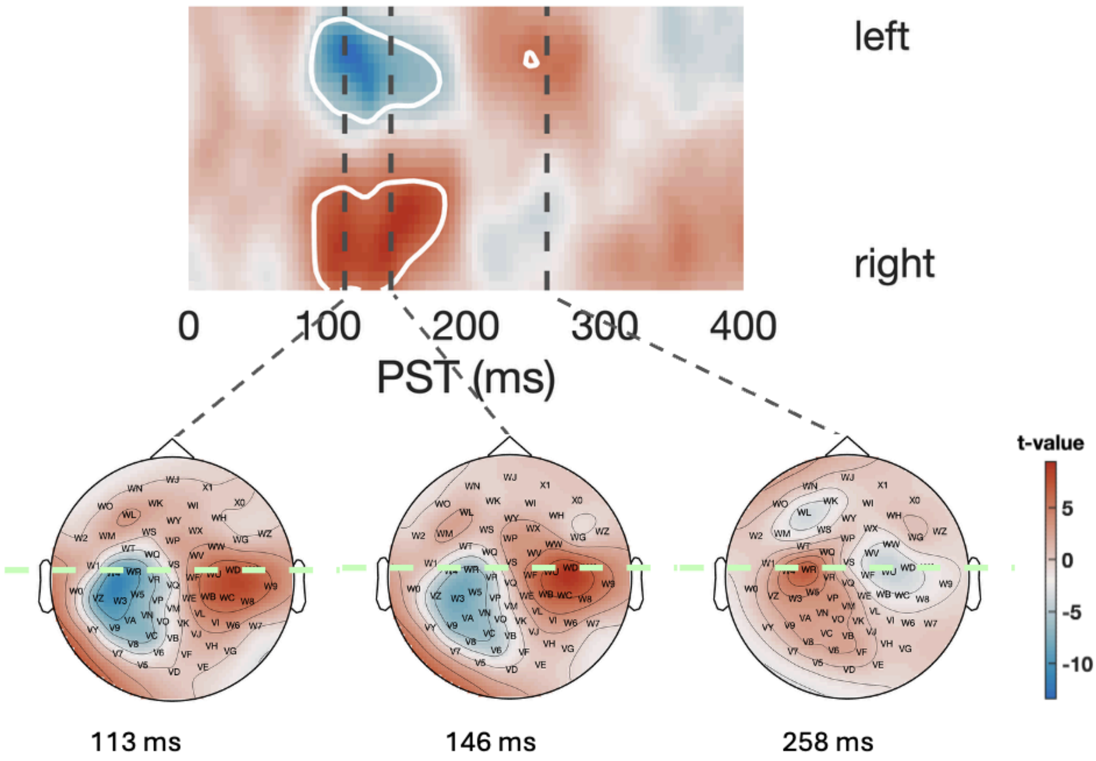

Figure 17: Statistical parametric map of the MMN event related radial field. Top: Time evolution of the t-values (see colorbar) for the left-to-right section indicated below. White contours indicate the significant clusters found. Bottom: Topography of the parametric map at the indicated times following stimulus.

OPM Development II / 96

Spin noise spectroscopy of an alignment-based atomic magnetometer

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Optically pumped magnetometers (OPMs) are revolutionizing the task of magnetic-field sensing due to their extremely high sensitivity combined with technological improvements in miniaturization which have led to compact and portable devices. OPMs can be based on spin-oriented or spin-aligned atomic ensembles which are spin polarized through optical pumping with circular or linear polarized light, respectively. Characterization of OPMs and the dynamical properties of their noise is important for applications in real-time sensing tasks. In our work, we experimentally perform spin noise spectroscopy of an alignment-based magnetometer. Moreover, we propose a stochastic model that predicts the noise power spectra exhibited by the device when, apart from the strong magnetic field responsible for the Larmor precession of the spin, white noise is applied in the perpendicular direction aligned with the pumping-probing beam. By varying the strength of the noise applied as well as the linear-polarization angle of incoming light, we verify the model to accurately predict the heights of the Larmor-induced spectral peaks and their corresponding linewidths. Our work paves the way for alignment-based magnetometers to become operational in real-time sensing tasks.

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Classification of Finger Movements Using OPM-Based MEG for Brain-Machine Interfaces

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Recently, Meta Platforms, Inc. reported that brain-machine interfaces (BMIs) based on magnetoencephalography (MEG) can achieve higher accuracy than those based on electroencephalography (EEG)[1]. Optically pumped magnetometers (OPMs), which have been actively developed for miniaturization and shield-free measurements, offer a promising noninvasive sensing solution for BMIs. In this study, we investigated whether hand movement tasks could be classified using MEG signals measured with OPM modules, with the goal of advancing BMI applications. A participant performed flexion and extension of either the thumb or the little finger inside a magnetic shield while MEG signals were recorded from sensors placed on the scalp. Simultaneously, myomagnetic signals were recorded from sensors on the forearm to determine movement onset. Independent component analysis was applied to extract brain-related components, followed by frequency analysis and principal component analysis (PCA), from which the first two principal components were used. Figure 1 shows the results of linear classification using a support vector machine (SVM), achieving a classification accuracy of approximately 67% for the two motor tasks. Future work will focus on improving classification performance by optimizing sensor position, increasing the number of sensors, and refining signal processing methods to enable classification of a broader range of tasks.

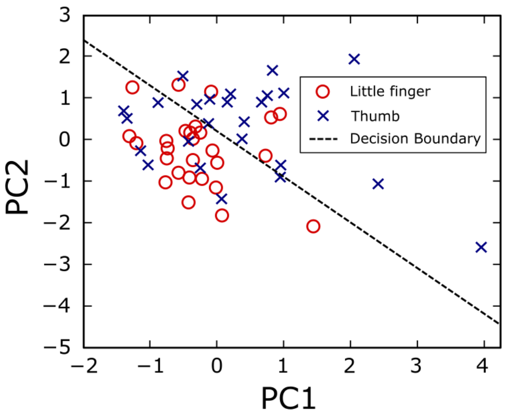

Figure 18: Classification of finger Movements by SVM.

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Quantum and Fundamental / 98

Self-compensating comagnetometer for exotic physics searches

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Self-compensating noble-gas–alkali-metal comagnetometers are highly sensitive to spin-dependent perturbations, making them useful tools for both inertial sensing and precision searches for physics beyond the Standard Model. To optimize these sensors for long-term measurements, required for such applications, we address two key challenges: robust calibration and long-term operational stability. We present a universal, frequency-resolved calibration method based solely on the comagnetometer's time-domain response to a step change in the magnetic field 1. This straightforward experimental procedure ensures accurate interpretation of both magnetic and nonmagnetic signals under a wide range of conditions.

Long-term stability of noble gas polarization is essential for continuous operation in precision experiments. In practice, this polarization decays over time due to magnetic field gradients, which lead to dephasing and relaxation of the nuclear spins. To mitigate this, we implement a method for zeroing magnetic field gradients inside the shielded environment, significantly extending polarization lifetimes. Additionally, we utilize a locked-loop control system that continuously maintains the system at optimal operating conditions, such as the compensation point, enabling uninterrupted measurements over extended periods 2.
We will present our our implementation of the noble gas polarization control and calibration routine in the context of our novel search for axion-like particles 3.

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Fast total field OPM for muscle measurements: first in vivo recordings in MyoQuant project

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The measurement of magnetic muscle signals requires sensors that go far beyond state-of-art in terms of their bandwidth and angular accuracy. In addition, practical applications require sensors that can tolerate elevated background fields. Magnetic muscle measurements were performed with the sensor developed within the MyoQuant project and promise new insights into the understanding of these signals. As part of this project, a compact demonstration setup is developed that utilises robust components to the highest possible extent, thus forms the basis for a future measuring instrument on the International Space Station or its follow-up.
These magnetometers are housed in a small half-open magnetic shield in which a test person can place arm or leg 1. To measure the magnetic muscle response, the sensors 2 are then placed along the muscle to be analysed, for example the one of the little finger (abductor digiti minimi, ADM). The sensor prototype is integrated into the transportable demonstrator, and a sensitivity of 0.3 - 0.9 pT/$\sqrt{\text{Hz}}$ in a bandwidth of 1 kHz is currently achieved. In this setup, the pilot sequential vector field recordings of ADM response were successfully performed, i.e. the first OPM-based measurement of muscle activity not limited by the sensor bandwidth and nonlinearity.
Based on the sensor concept proposed by the PTB, a miniaturised, fibre-coupled sensor head is being designed and constructed at the FBH. Additively manufactured technical ceramics serve as the chassis for the alkali vapour cell and the optical and electrical components, which are precisely aligned and bonded to the ceramic substrate using hybrid microintegration. Broader range of the muscle measuremnts with array of such sensors is planned.

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Poster Session and Buffet / 100

Toward an Optically Pumped Magnetometer Magnetoencephalography System with Full Head Coverage

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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 2 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 implemented a light distribution system for our two-color pump/probe OPM. Finally, we will discuss efforts to develop custom control hardware and software, OPM array calibration approaches, an MSR with magnetic field control, installation of the OPMs into the MSR, and hopefully our first human measurements with the system.
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Poster Session and Buffet / 101

Progress in Inductive Detection

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Radio-frequency (rf) atomic magnetometers (AM) can measure oscillating magnetic fields (1 kHz-1 MHz range) with fT/√Hz sensitivity and are 2D sensors. Magnetic induction tomography (MIT) measurements require sensitive magnetometers, e.g., for use in the non-destructive testing of pipework and defect detection. Experimental work, verified with COMSOL simulations, shows how changing rf field polarisations across a sample affect the output of the magnetometer, giving the impression that symmetric samples (with no defect) appear to be asymmetric (defective). This full understanding is necessary as the drive towards commercialising the technology approaches.
Work is also presented on developing the two-photon rf AM, which allows us to operate at low frequencies (<1 kHz). All spectral components of the two-photon process are identified, which result from the non-linear interactions between the rf fields and atoms. For the first time, a method for the retrieval of the two-photon phase information, which is critical for inductive measurements, is also demonstrated. Furthermore, a self-compensation configuration is introduced, whereby high-contrast measurements of defects can be obtained due to its insensitivity to the primary field, including using simplified instrumentation for this configuration by producing two rf fields with a single rf coil.
Statistical methods and machine learning can be used to increased data acquisition rate through data reconstruction for inductive measurements, which is vital for real working environment, e.g. in process and field testing. This work will discuss the advantages and disadvantages of this method for defect detection.
Finally, results from our prototype AM is presented, where the sensor is used for the non-destructive testing of defects in metallic samples.

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Enabling Vector Magnetic Field Measurements in a Single-Axis Optically Pumped Magnetometer

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Optically Pumped Magnetometers (OPM) have been a promising technology for magnetometry. Zero-field OPMs have evidenced a capability to measure magnetic fields as small as 10 fT 1 with sensitivity levels ranging from 1 fT/√Hz 2. Moreover, the practical advantages of the OPM include its compact size and independence of the cryogenic environment, unlike SQUID-based magnetometers 3. These specifications make the OPM one of the most sought-out technologies for quantum magnetometry [4]. In fact, OPM fits well for biomedical applications such as magnetoencephalography as well, because of its flexibility to fix all subject sizes [5].

Traditionally used OPMs were built as single-axis magnetometers. The single-axis magnetometer measures one of the components of the magnetic field aligned with the direction of the sensor. If the sensor is misaligned with the direction of the magnetic field, it misses some of the information, such as the fields tangential to the sensor. Moreover, the tangential fields introduce measurement errors along the axis. To address this, the triaxial magnetometer [6], which measures the full vector magnetic field, is considered a better alternative. However, apart from the merits, there exist a few non-ignorable points, such as this complex setup requires a beam splitter which halves the power of the laser and increases the noise floor [7]. This noise floor surpasses the noise floor of the single-axis magnetometer [8]. Furthermore, the single-axis magnetometer is cost-effective and compact compared to the triaxial magnetometer.

This theoretical work proposes a novel approach to measure the total magnetic field using a single-axis magnetometer rather than a triaxial magnetometer. While single-axis OPM measurements are generally performed by analysing the principal frequency component of the polarisation signal, we show that the higher-order frequency components contain information on magnetic field components transverse to the measurement axis. Through the development of an accurate OPM model, we characterise this additional information and propose a novel post-processing technique allowing the extraction of the full vector magnetic field in a single-axis measurement.

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Welcome

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Closing remarks

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Introduction to OPM

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MEG with OPM

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Measurement of Transient Magnetic Fields Using a Free- Induction-Decay Atomic Magnetometer

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The Transient Electromagnetic Method (TEM) has attracted significant interest because of its non-destructive evaluation, rapid response, and environmentally adaptable. In traditional TEM systems, the signal acquisition module generally utilizes multi-turn induction coils. Based on Faraday's law of electromagnetic induction, these coils detect the secondary eddy currents induced by the primary magnetic field to identify metallic conductors. Nevertheless, it is difficult to measure the small electromotive force induced by a weak low-frequency magnetic field using such method. This constraint limits the potential for sensitivity enhancement and applications of TEM systems.

In this work, we present an alternative technique for measuring transient magnetic fields. It employs a free-induction-decay (FID) atomic magnetometer as the core sensor, replacing conventional induction coils to enhance the capability of extraction of weak signals. Furthermore, an optically-pump-enhanced scheme is utilized 1, which employs the primary pulse to increase the polarization of the atomic ensemble. This enhancement amplifies the FID signal amplitude, thereby improving the measurement sensitivity. The instantaneous-phase retrieval method 2 is applied to reconstruct the eddy-current fields. Experimental results show the successful measurement of the eddy-current fields of copper, aluminum, zinc, and lead. This work exhibits considerable potential for advancing high-precision TEM systems.

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Poster Session and Buffet / 111

Exploiting non-uniform field effects for quantum sensing

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Miniature atomic vapor cells are a fundamental component in future-focused field-deployable quantum technology development. Here, we explore the physics of diffusive alkali metal-noble gas spin systems magnetization in a mm-sized wafer-fabricated vapor cell, engineered with an eye towards room temperature atomic magnetometry, co-magnetometry and gyroscope setups. Through a systematic survey of magnetic resonance spectra over a range of optical pump powers, vapor cell temperatures, and experimental geometry, we identify regimes of optimal sensor operation 2. We discuss the specific spectral features effected by non-uniform electromagnetic fields in these systems and demonstrate a symmetry-breaking phase transition of the noble gas using engineered optically induced linear field gradients [2, 3, 4]. We further investigate the use of more complex spatial modes of light to interface the spatial diffusive modes of alkali atoms, demonstrating temporal and spatial manipulation of spin precession and relaxation. These results offer insight into the complex physics of collective atomic spins displayed by miniature vapor cells and will drive fundamental advances for metrology and sensing.

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Poster Session and Buffet / 112

A ^{199}Hg Co Magnetometer System for the n2EDM Experiment

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The n2EDM experiment at the Paul Scherrer Institute searches for the electric dipole moment (EDM) of the neutron with a baseline sensitivity of ˜1×10^{-27} e·cm. Precise monitoring of the average magnetic field experienced by the neutrons is required to guard against systematic shifts on the EDM measurement that cannot be mitigated otherwise. The magnetic field monitoring is achieved using optically pumped ^{199}Hg co-magnetometers operating in the same storage volumes as the neutrons. The reduced neutron statistical uncertainty imposes a 25 fT uncertainty level on the magnetic field measured by t he co-magnetometers.
This poster presents the design, implementation, and performance of the mercury co magnetometer system.

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Muon Spin Rotation - Magnetic fields inside solids

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