Talks

Title	A Pound–Drever–Hall Cavity OPM for Magnetotactic Bacteria Measurements
Authors	Christopher Kiehl[1], María Hernández Ruiz[1], Cristina Sastre-Jachimska[1], Vito Giovanni Lucivero[1, 2], Morgan W. Mitchell[1, 3] [1]ICFO - Institut de Ciències Fotòniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels (Barcelona), Spain [2]Dipartimento Interateneo di Fisica, Università degli Studi di Bari Aldo Moro, 70126 Bari, Italy. [3] ICREA – Institució Catalana de Recerca i Estudis Avançats, 08010 Barcelona, Spain

The sensitivity of miniaturized optically pumped magnetometers (OPMs) is often limited by weak atom–light coupling, which can be enhanced using an optical cavity. We present a Pound–Drever–Hall (PDH) cavity OPM based on a microfabricated rubidium vapor cell, achieving a noise floor of 22.2 pT/√Hz and a minimum instability of 47 pT at an averaging time of 6 s [1]. We discuss how the cavity design and operating conditions can be improved and quantify the optimal sensitivity enhancement achievable with a cavity-based OPM [2]. We then apply the OPM to measurements of concentrated populations of the magnetotactic bacterium Magnetospirillum gryphiswaldense strain MSR-1 [1]. The measurements reveal non-exponential relaxation dynamics and their evolution during settling and evaporation, providing information about variations in bacterial magnetic moments and rotational damping coefficients. To our knowledge, these are the first direct observations of such magnetic inhomogeneities and long-term deviations from exponential relaxation in magnetotactic bacterial populations.

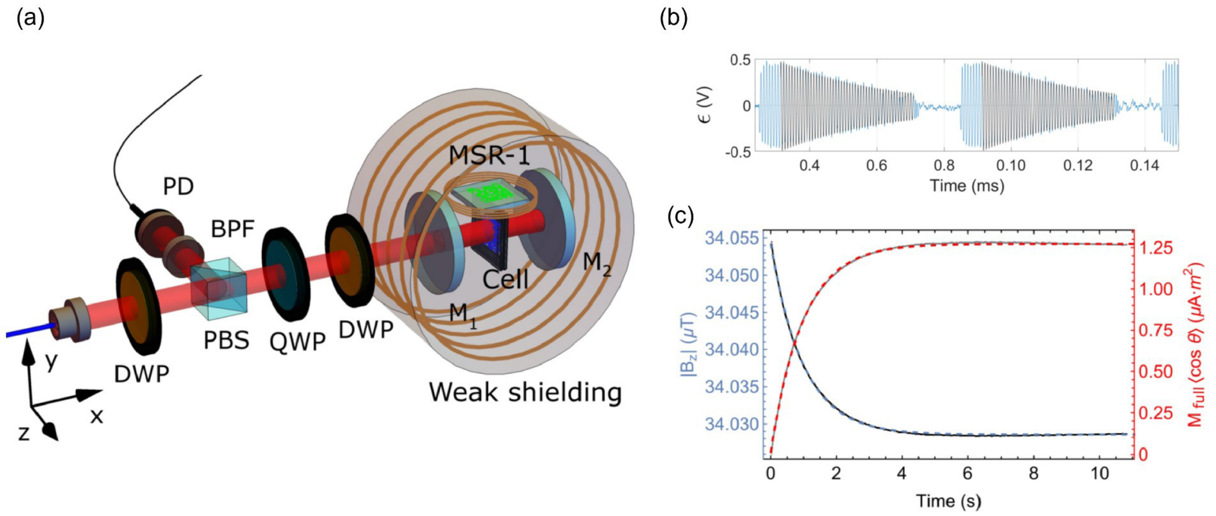

Figure 1: (a) PDH-OPM schematic used for the study of MSR-1 populations. (b) PDH OPM free induction decay measurements. (c) The observed magnetic field strength during MTB relaxation and their inferred magnetization.

[1] M. H. Ruiz, C. Kiehl, V. G. Lucivero, M. W. Mitchell, *EPJ Quantum Technol.* **13**, 45 (2026)

[2] C. Kiehl, M. H. Ruiz., C. Sastre-Jachismka, M. H. Mitchell, *Sensitivity Scaling and Limits of Cavity Enhancement in Miniaturized Optically Pumped Magnetometers,* in preparation.

Title	Quantum Noise and Quantum Enhancement in Hybrid and Miniaturized Optically Pumped Magnetometers
Authors	Diana Mendez-Avalos[1], Aleksandra Sierant[1], Theo Louzada Meireles[1], Santiago Tabares Giraldo[1], Morgan W. Mitchell[1,2] [1] ICFO – The Institute of Photonic Sciences, Barcelona, Spain [2] ICREA - Institució Catalana de Recerca i Estudis Avançats [3] Instituto de Física, Universidade de São Paulo, São Paulo, Brazil

We study quantum-enhanced sensitivity in two optically pumped magnetometer (OPM) platforms. The first platform is a squeezed-light-probed hybrid OPM (hOPM), where we investigate the quantum noise mechanisms that limit continuously operating multiparameter quantum sensors in the quantum-noise-limited regime [1,2]. The second platform is a MEMS vapor cell Bell-Bloom magnetometer, where we pursue quantum enhancement through conditional spin squeezing generated by quantum non-demolition (QND) measurement, with the goal of surpassing the sensitivity of the atomic-noise-dominated region. We generate a highly polarized spin ensemble using an amplitude-modulated pumping scheme to reach the light-narrowing regime [3]. Figure 1 summarizes these two directions: squeezed-light-enhanced sensitivity in the hOPM sensor; and the atomic noise spectra, and quantum-noise-limited sensitivity measured for the MEMS Bell-Bloom platform.

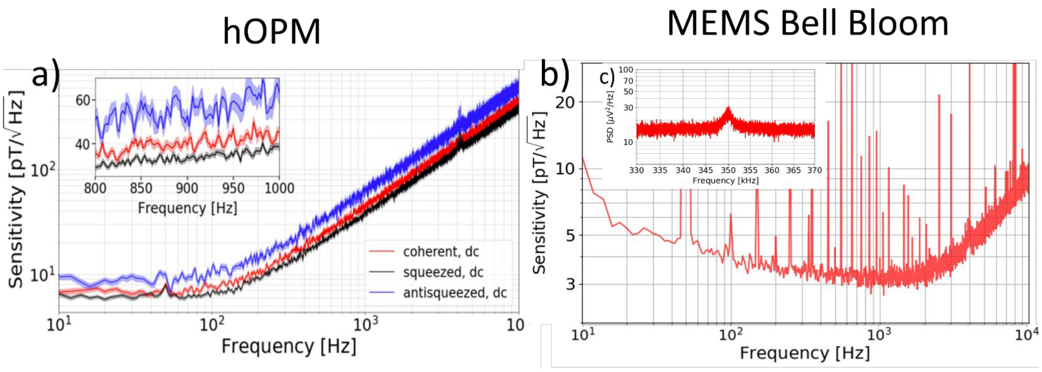

Fig. 1. Measured sensitivity for a) quantum-enhanced hOPM and b) MEMS Bell-Bloom. c) measured MEMS spin noise spectra.

[1] A. Sierant, D. Mendez-Avalos, S. Tabares, M. Mitchell, arXiv:2602.05991 (2026)
[2] A. Sierant, D. Mendez-Avalos, S. Tabares, M. Mitchell, arXiv:2506.08190 (2025)
[3] D. Mendez-Avalos, T. Meireles, M. Mitchell, A. Sierant, arXiv: 2604.26721(2026)

Title	Laser-written vapor cells for chip-scale optical magnetometry
Authors	Andrea Zanoni[3], Kostas Moloudakis[2], Michael C.D. Tayler[2], Giacomo Corrielli[5], Roberto Osellame[5], Morgan W. Mitchell[2,6] and <u>Vito Giovanni Lucivero</u>[1,2,3] [1] Dipartimento Interateneo di Fisica, Università degli Studi di Bari Aldo Moro, 70126 Bari, Italy [2] ICFO- Institut de Ciències Fotòniques, 08860 Castelldefels (Barcelona), Spain [3] QSENSATO Srl, Via Giovanni Amendola 173, 70126 Bari, Italy [4] Dipartimento di Fisica — Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milano, Italy [5] Istituto di Fotonica e Nanotecnologie (IFN) — Consiglio Nazionale delle Ricerche (CNR), Piazza Leonardo da Vinci 32, 20133 Milano, Italy [6] ICREA- Instituci Catalana de Recerca i Estudis Avan¸cats, 08010 Barcelona, Spain

We introduce laser-written vapor cells (LWVCs), a technology based on femtosecond laser writing followed by chemical etching (FLICE), that allows arbitrarily shaped 3D hollow microstructures. In the first experiment [1] we demonstrate sub-Doppler saturated absorption spectroscopy and an optically pumped magnetometer (OPM) with elliptically polarized light. In a second experiment [2] we report a sensitivity of 1pT/√Hz at 10 Hz using a zero-field-resonance (ZFR) OPM and 0.75 amg of N_2 buffer gas in a sub-mm-width laser-written channel (Fig. 1). Finally, I'll present the recent progress towards the integration of this technology with PICs and microfluidic channels in all-glass atomic-photonic chips for quantum sensing and metrology applications.

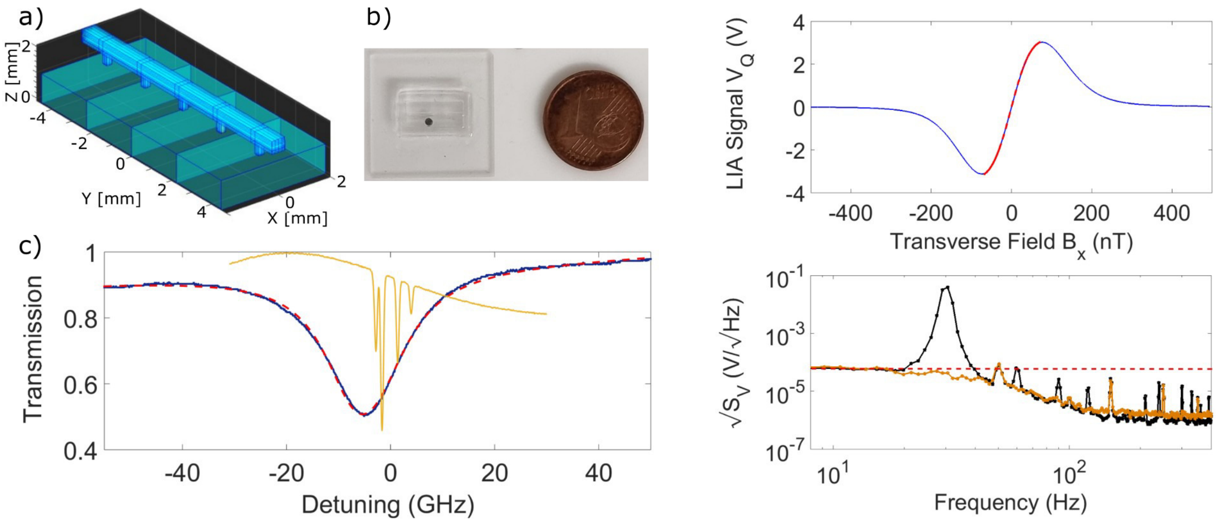

Figure 1: Left a) Design of the LWVC with a top 9 mm-long sensing micro-channel. b) LWVC after fabrication by FLICE. c) Normalized transmission (blue) through the LWVC and a Rb reference vapor cell (yellow) evacuated to 10^{-8} Torr. Right LIA quadrature output signal (Top) and amplitude noise density (Bottom) in a ZFR-OPM using a LWVC. The LIA noise SV, converted to equivalent magnetic noise using the slope of the LIA signal, implies a magnetic sensitivity of 1pT/√Hz, shown by the red dashed line.

[1] V.G. Lucivero, A. Zanoni, G. Corrielli, R. Osellame and M. W. Mitchell, Laser-written vapor cells for chip-scale atomic sensing and spectroscopy, Opt. Express, 30, 27149-27163 (2022).
[2] A. Zanoni, K. Mouloudakis, M. C. D. Tayler, G. Corrielli, R. Osellame, M. W. Mitchell and V. G. Lucivero, Picotesla optically pumped magnetometer using a laser-written vapor cell with sub-mm cross section, *J. Appl. Phys.* 136 (14): 144401 (2024) https://doi.org/10.1063/5.0230180

Title	Quantum-Enhanced Magnetometry via Spin Nonequilibrium Criticality
Authors	Guzhi Bao[1], Ding Huang[1], Minwei Shi[1], Keye Zhang[2], Weiping Zhang[1] [1] Shanghai Jiao Tong University, Shanghai, China [2] East China Normal University, Shanghai, China

The sensitivity of quantum sensors is fundamentally constrained by the standard quantum limit (SQL) arising from intrinsic quantum fluctuations. While non-classical resources like squeezing or entanglement can surpass this limit, their utility is often restricted by the extreme fragility of entangled states and the complexity of their preparation. Quantum criticality offers a compelling alternative by harnessing divergent susceptibility to amplify signals without requiring fragile non-classical resources. However, the practical benefit of this approach has remained controversial due to the potential for the simultaneous amplification of quantum noise. Here, we demonstrate a universal protocol for noiseless critical sensing by engineering a light-driven atomic ensemble near a dynamical critical point. Analogous to a Kapitza pendulum near its inverted orientation, the spin system enters a non-equilibrium regime where the signal susceptibility diverges while the quantum noise periodically recedes to its coherent baseline. We demonstrate a 3.3 dB metrological gain over the SQL in an atomic magnetometer. Our implementation exhibits intrinsic robustness against common experimental imperfections such as detection losses, establishing non-equilibrium critical dynamics as a practical and versatile paradigm for surpassing the fundamental limits of quantum sensing.

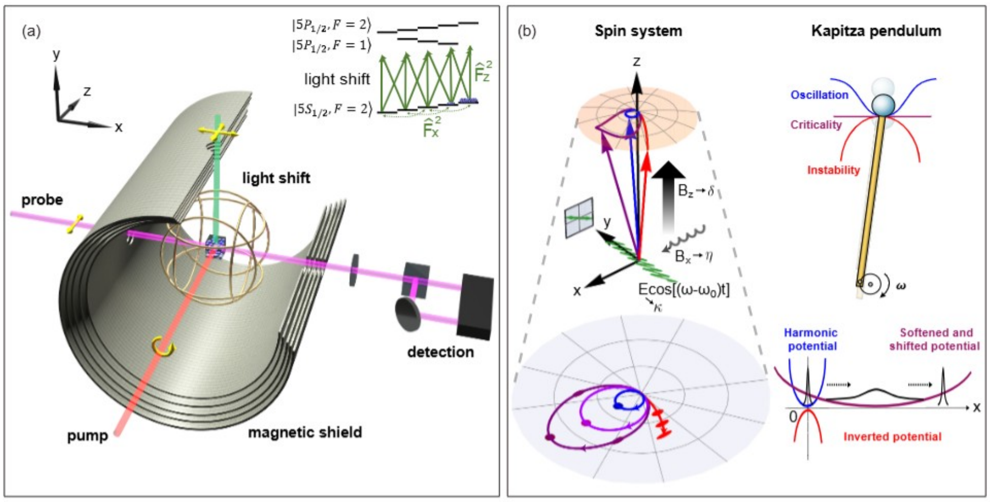

Figure 1: Experimental setup and operating principles of the criticality-enhanced atomic magnetometer.

Title	Quantum Noise Analysis and Suppression in Atomic Magnetometer
Authors	Jia Kong

Magnetic field detection plays a critical role in aerospace, defense, biomedical applications, and other fields, and is often regarded as a key indicator of technological capability. Consequently, continuous improvement of magnetometer performance remains an important research direction.

In principle, the ultimate sensitivity of atomic magnetometers is limited by quantum noise from both atoms and light. Quantum squeezing of atomic spin states or optical fields therefore provides a promising route to surpass the standard quantum limit and enhance measurement sensitivity. However, high-sensitivity magnetometers typically operate with high-density atomic ensembles, where strong interactions and significant optical absorption pose substantial challenges for the implementation and observation of quantum-enhanced effects. In this context, a detailed understanding of quantum noise mechanisms is essential for both noise suppression and the underlying physical interpretation.

Here, I present our recent work on quantum-enhanced atomic magnetometry [1,2], quantum noise analysis in the spin-exchange relaxation-free (SERF) regime [3], and a practical framework for weak-signal estimation [4,5]. These results demonstrate the compatibility of quantum squeezing with atomic sensing platforms and highlight their potential advantages for precision measurement applications.

[1] Charikleia Troullinou*, Ricardo Jiménez-Martínez, **Jia Kong***, Vito Giovanni Lucivero, and Morgan W. Mitchell,Physical Review Letters, 127(19) (2021).

[2] **Jia Kong***, Ricardo Jimenez-Martınez, Charikleia Troullinou, Vito Giovanni Lucivero, Géza Tóth, and Morgan W. Mitchell*, Nature Communications 11:2415 (2020).

[3] K. Mouloudakis*, **J. Kong***, A. Sierant, E. Arkin, M. Hernández Ruiz, R. Jiménez-Martínez, and M. W. Mitchell, Physical Review A 109, L040802 (2024).

[4] **Jia Kong**, Yaping Feng, Yihan Wang, Qingwei Wang, and Xiao-Ming Lu, Physical Review Applied 24, 064001 (2025).

[5] Yihan Wang, Xiaofeng Jin, Yuchuan Ming, Jianxiang Miao, Xiao-Ming Lu*, M. W. Mitchell, **Jia Kong***, arXiv:2605.17784 [quant-ph] (2026).

Title	Fidelity of deep source localization in MEG with varying degrees of simultaneous cortical activity: a simulation study comparing SQUIDs and OPMs
Authors	Line Kruse[1], Laura Bock Paulsen[1], Lauri Parkkonen[2], Lau Møller Andersen[1,3] [1] Department of Linguistics, Cognitive Science and Semiotics, Aarhus University, Denmark [2] Department of Neuroscience and Biomedical Engineering, Aalto University, Espoo, Finland [3]Center of Functionally Integrative Neuroscience (CFIN), Aarhus University and Aarhus University Hospital, Denmark

Source modeling of non-cerebral sources from MEG recordings is challenging due to the complex cytoarchitecture of these structures and their distance to the sensors. Further, the signal generated by deep sources can in many cases be explained by distributed patterns of simultaneous cortical activation. However, experimental paradigms can be designed to minimize simultaneous direct cortical activation by using e.g. omission target events or direct neuromodulatory stimulation. This study aims to assess the extent to which non-cerebral source localization improves in such cases, testing how detection of sources varies depending on the strength and site of simultaneous cortical activation.

As an example, thalamic activity was simulated with increasing SNR from 1.2 to 8.5, while adding increasing simultaneous activation in primary visual cortex (V1) from SNR of 0 to 19.8. Region Localization Error (RLE) was computed for each of the two sources, along the gradient of increased activation in both the non-cerebral and cerebral source. Preliminary results based on SQUIDs, showed that while weak thalamic activations (SNR=1.2) can be well localized in isolation (RLE=15mm), adding even weak (SNR=1.3) simultaneous activity in V1 drives the full source estimate towards the V1 (RLE=60mm). However, for stronger thalamic signals (SNR=3.2) the estimated thalamic source is preserved regardless of the simultaneous signal strength in V1 (RLE=7.5mm). This study compares these results to the same simulations using OPM sensor arrays, and will include four non-cerebral sources (cerebellum, thalamus, basal ganglia and hippocampus), and three cerebral sources (V1, A1, S1). Additionally, we compare source modeling using MNE and LCMV Beamformer. This study will 1) provide evidence on the regional distortion impact of simultaneous activity in cerebral and non-cerebral sources in SQUID vs. OPM systems and 2) allow optimization of experimental and analytical designs in which subcortical sources are of interest.

Title	Evaluating Localization Accuracy and the Impact of Movement in the HEDscan OPM-MEG System
Authors	Svenja Knappe[1,2], George O'Neill[1], Orang Alem[1,2], Tyler Maydew[1], Teresa Cheung[1,3,4] [1] FieldLine Medical, Colorado, USA [2] Paul M. Rady Department of Mechanical Engineering, University of Colorado, USA [3] Simon Fraser University [4] Fraser Health Authority

Accurate source localization is a cornerstone of both clinical and cognitive magnetoencephalography (MEG). This study evaluates the localization capabilities of the FieldLine HEDscan OPM system, focusing on the critical interplay between sensor calibration, phantom validation, and validation during movement. High-fidelity source localization inherently depends on precise sensor calibration and the accurate determination of each sensor's position within the array. We detail the system's closed-loop operation—which provides a +/- 150 nT dynamic range without the need for active cancellation panel coils [1] and HEDscan OPM's smart helmet technology that automatically localizes the sensor positions. We demonstrate how these parameters directly feed into our validation framework using both a 4D Magnes 3600 WH cryo-MEG wet saline phantom and a novel printed circuit board (PCB) dry phantom. The wet phantom studies demonstrated that both the HEDscan OPM and the 4D cryo-MEG systems achieved localization accuracies well below the manufacturer's specifications for the phantom. Statistical analysis shows no significant difference between the localized dipole moments of the two systems. Furthermore, the custom PCB phantom provided a rigid ground truth, achieving median relative localization errors of approximately 0.65 mm for current dipoles and demonstrating the spatial resolution required to resolve distinct sources separated by only 2 mm.

Finally, we address the complex effects of movement on localization accuracy. Motion through ambient magnetic field gradients can introduce dynamic artifacts, such as cross-axis projection errors [3], and we examine how effectively the system's closed-loop background field compensation maintain localization integrity. These findings provide a comprehensive technical validation of the HEDscan OPM system, underscoring its robustness and precise spatial resolution for neuroimaging.

[1] O. Alem et al., Frontiers in Neuroscience 17, (2023).
[2] H. Schofield, R.M. Hill, L. Rier et al., Imaging Neuroscience 3, (2025).
[3] S.E. Robinson et al., NeuroImage 262, 119559 (2022).

Title	OPM-MEG in a compact magnetic shield
Authors	Mikael Grön, Paavo Hietala, Olli Pikkarainen, Markus Henttonen, Eelis Eklund, Eemeli Luostarinen, Joonas Iivanainen, Lauri Parkkonen Department of Neuroscience and Biomedical Engineering, Aalto University, Espoo, Finland

Typically, OPM-MEG systems are deployed in magnetically shielded rooms (MSRs), similarly to those used with conventional SQUID-MEG systems. However, OPM systems have smaller footprints than SQUID systems, so for OPMs a compact person-sized shield would be a sufficient, cost-effective alternative to a large MSR.

We have designed, together with the shield manufacturer (Vacuumschmelze GmbH & Co. KG, Hanau, Germany), a 2-layer (mu-Al-mu) cuboid-shaped person-sized compact shield. The five inner walls of the shield are covered by electromagnetic coils printed on circuit boards. These large coils can generate all homogeneous and first-order gradient magnetic fields to dynamically compensate environmental fields. Gradient coils are run statically, while homogeneous coils are run in a PI-controlled feedback loop with four reference QZFM Gen-3 OPMs (QuSpin Inc., Louisville, CO, USA). Our custom-designed OPM helmet includes 99 depth-adjustable slots for OPMs and five small electromagnetic coils. Together with the large coils, these coils are used to co-register the OPMs to the helmet [1,2], which is optically co-registered to the subject [3].

After degaussing, the DC magnetic field inside the shield is 5.3 nT with a peak-to-peak drift of 75 pT. Using active shielding, these fields can be reduced to 1.0 nT and 12 pT, respectively. The passive shielding factor was 50 dB at 0.1 Hz and 70 dB at 10 Hz, while the active shielding factor was 30 dB at 0.1 Hz. Using six OPMs we localised six dipoles of a dry phantom with a mean error of 1.8 mm, 1.2° and 11% for the location, orientation and amplitude, respectively. These results show that high-quality OPM-MEG can be performed with an easy-to-site, compact system.

[1] J. Iivanainen, Sensors, 22(8), p.3059 (2022).
[2] C. Pfeiffer, NeuroImage, 212, p.116686 (2020).
[3] R. Zetter, Scientific Reports, 9(1), p.5490 (2019).

Title	AI-Driven Adaptive Noise and Artifact Mitigation for Wearable OPM-MEG
Authors	Jing Xiang[1*], Fawen Zhang[2], Jiang Yang[3], Elena Harris[1] *[1]Cincinnati Children's Hospital Medical Center, Cincinnati, OH, USA* *[2]University of Cincinnati, Cincinnati, OH, USA* *[3] University of Kentucky, Lexington, KY 40536, USA,*

Wearable optically pumped magnetometer-based magnetoencephalography (OPM-MEG) enables high-sensitivity brain recordings with unprecedented flexibility, but its performance remains highly susceptible to environmental interference, motion-induced artifacts, and sensor instability, particularly in a pediatric setting. Addressing these challenges is critical for advancing OPM-MEG toward real-world and clinical applications.

In this work, we present an AI-driven adaptive signal processing framework for robust noise and artifact mitigation in wearable OPM-MEG. Building upon our prior work [1,2], the proposed approach integrates data-driven models with physics-informed constraints to suppress non-neuronal interference while preserving physiologically meaningful signals. Specifically, we develop deep learning–based denoising modules that operate jointly in spatial and temporal domains, enabling adaptive separation of brain activity from structured environmental noise and motion-related artifacts. These models are embedded within a real-time processing pipeline that incorporates frequency-encoded source imaging (FESI) to further enhance source-level robustness.

We evaluated the framework on OPM-MEG recordings acquired under both controlled and semi-naturalistic conditions, demonstrating substantial improvements in signal-to-noise ratio, artifact suppression, and source localization stability compared with conventional filtering and regression-based methods. Importantly, the proposed system generalized across varying sensor configurations and noise environments, supporting flexible deployment in wearable settings.

Our results showed that AI-driven adaptive noise and artifact mitigation enabled wearable OPM-MEG deployment in demanding pediatric settings, significantly improving signal quality in recordings from young children prone to movement. In this workflow, raw OPM sensor data underwent adaptive AI-based noise and artifact suppression, followed by FESI for source reconstruction. The system continuously updated model parameters to enhance robustness against motion and environmental interference, ultimately enabling reliable, real-time brain source imaging and downstream applications.

This work highlights the transformative role of AI in overcoming key limitations of OPM-MEG and establishes a scalable pathway toward reliable, real-world neuroimaging. The proposed framework facilitates next-generation applications in mobile brain monitoring, brain–computer interfaces, and clinical neurophysiology.

Reference:

[1] J. Xiang et al., J. Integr. Neurosci. 21, 145 (2022).
[2] J. Xiang et al., Brain Sci. 13, 663 (2023).

Title	Chip-Scale Atomic Magnetometers for Ultra-Weak Magnetic Field Measurement: From MEG to Ultra-Low Field NMR
Authors	Yao Chen, Libo Zhao School of Instrument Science and Technology, Xi'an Jiaotong University State Key Laboratory for Manufacturing Systems Engineering, Xi'an Jiaotong University

Optically pumped magnetometers (OPMs) have demonstrated exceptional sensitivity for ultra-weak magnetic field measurements, paving the way for advanced applications such as magnetoencephalography (MEG) and ultra-low field nuclear magnetic resonance (ULF-NMR). However, the bulky nature of traditional table-top setups restricts their deployment in highly integrated, multi-channel, or portable systems. Here, we present the development of a highly integrated, chip-scale atomic magnetometer that leverages novel microfabrication techniques[1,2]. To address the opacity issue of traditional silicon-based cells, we developed a multi-faceted transparent MEMS alkali vapor cell[3]. Furthermore, we employed a femtosecond laser welding technique for cell sealing[4], which successfully preserves the octadecyltrichlorosilane (OTS) anti-relaxation coatings. For compact magnetic field control, we integrated MEMS bi-planar coils, enabling three-dimensional magnetic field manipulation within a miniaturized footprint. The fully packaged sensor features a compact size of just 45 mm × 15 mm × 12 mm and achieves a magnetic field sensitivity of 15 fT/√Hz[1]. Finally, we demonstrate the practical application of this sensor by constructing a ULF-NMR spectrometer, which was successfully utilized to detect and analyze the concentration of copper sulfate ($CuSO_4$) ions in aqueous solutions. Our work provides a scalable and high-performance solution for the next generation of brain magnetic field imaging and biochemical ULF-NMR analysis.

[1]Ma Y, Chen Y, Yu M, Wang Y, Guo J, Yang P, et al. Chip-scale quantum magnetometer empowered by reflector-integrated all-in-one atomic vapor cell. Science China Physics, Mechanics & Astronomy 2026, 69(2): 220313.
[2] Wang Y, Yu M, Chen Y, Ma Y, Han X, Xia Y, et al. The fabrication of MEMS alkali metal vapor cells based on ultrafast laser welding for single beam magnetometer. Microsystems & Nanoengineering 2025, 11(1): 153.
[3] Yu M, Chen Y, Wang Y, Han X, Luo G, Zhao L, et al. Microfabricated Atomic Vapor Cells with Multi-Optical Channels Based on an Innovative Inner-Sidewall Molding Process. Engineering 2024, 35: 46-55.
[4]Ma Y, Chen Y, Yu M, Wang Y, Lu S, Guo J, et al. Ultrasensitive SERF atomic magnetometer with a miniaturized hybrid vapor cell. Microsystems & Nanoengineering 2024, 10(1): 121.

Title	A robust and rapid Dual-Frequency Counter for FID magnetometers and Co-Magnetometers
Authors	Huanghui Deng[1],Haoyu Liu[1] , Xueke Wang[1], Jiang He[1], Wei Gao[1], Kai Liu[1], Bing Miao[1], Dong Sheng[1], Yuming Wang[1] University of Science and Technology of China, Hefei, China[1]

Conventional nonlinear fitting methods for FID signals are slow in computation time. Previously, our group have demonstrated a rapid frequency counter based on Hilbert transform [1]. However, this method works only for the signal with a single frequency. In this work, we proposes a robust multi-frequency FID signal estimation algorithm based on discrete-time-Fourier-transform (DTFT) interpolation. This method simultaneously reduces computational complexity, improves robustness against noises, and can be implemented in embedded platforms such as FPGAs. While maintaining a high estimation precision. the calculation time is within 200 μs for data with a length of 4096, achieving real-time frequency estimation of real time signals.

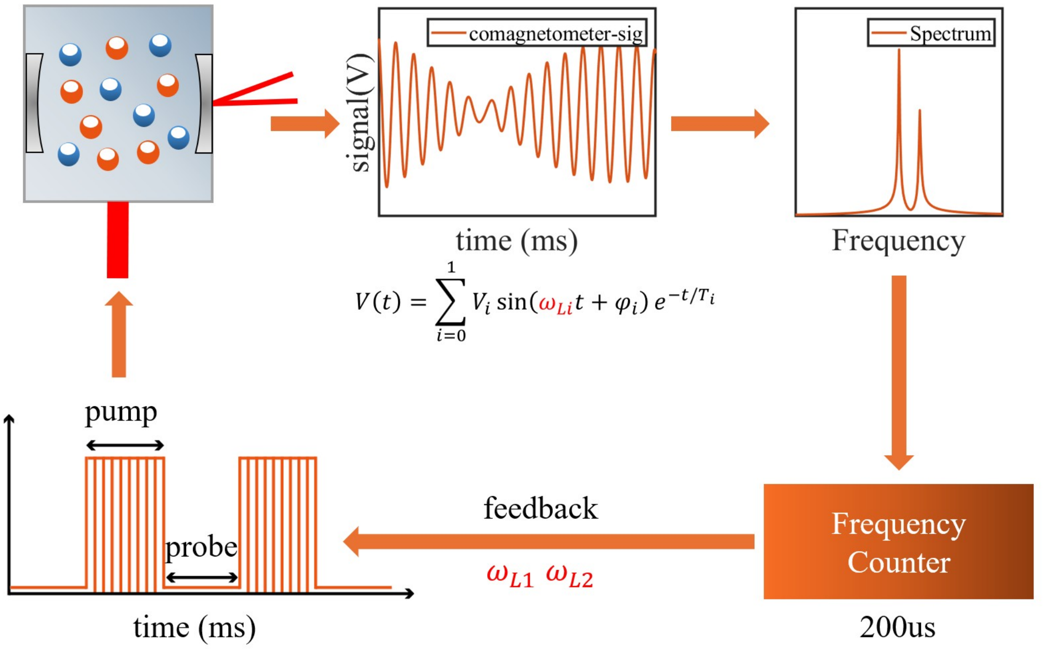

Figure 1: Application of Dual-Frequency Counter in a closed-loop FID Co-magnetometers

[1] T. Gong, IEEE Trans. Instrum. Meas., vol. 74, pp. 1-6 (2025)

Title	Helium-3 Magnetometry for Ultra-Weak Magnetic Field Measurement and Uncertainty Evaluation
Authors	Peiyuan Liu[1], Zhiyuan Jiang[1], Jianan Qin[1] [1] National Institute of Metrology, China

Helium-3 magnetometry provides an absolute approach for magnetic-field measurement, in which the field is determined from the Larmor precession frequency of polarized helium-3 nuclear spins and the helium-3 gyromagnetic ratio. This method is suitable for developing a traceable magnetic-field reference for high-sensitivity magnetometers and weak-field measurement systems.

We report recent progress on a helium-3-based absolute magnetic-field measurement system focused on ultra-weak magnetic fields and uncertainty evaluation. The system consists of a multi-layer magnetic shield, three-axis field coils, optical pumping, free-induction-decay signal detection, and low-noise data acquisition. Tens-of-pT magnetic fields have been measured, and a helium-3 spin relaxation time of approximately 50 hours has been achieved, showing the potential for long-term stable measurements in an ultra-weak magnetic environment.

An uncertainty evaluation was performed for the ultra-weak magnetic-field measurements. The analysis considers the main uncertainty contributions in the measurement process and provides a quantitative basis for assessing the reliability of the helium-3 spin-precession magnetometry system.

Title	Developing Optically Pumped Magnetometers for GNSS-Aided Navigation
Authors	Tiantian Zhang, Rafael Rothganger de Paiva, Dmitrii Grigorev, Konstantin Katamadze, Hitheswar Prasad, Philip Verwegen, Tingpeng Luo, Raquel Flores, Karsten Pyka, Rene Reimann

Global Navigation Satellite Systems (GNSS) underpin modern positioning and navigation, yet their vulnerability to jamming, spoofing, and signal denial in contested environments poses a growing operational risk. Magnetic anomaly navigation — in which a vehicle's position is estimated by matching real-time measurements of Earth's magnetic field against a geophysical reference map — offers a passive and unjammable complement to GNSS. Realising this capability requires sensors of sufficient sensitivity and stability to resolve subtle magnetic field variations in real-world environments, a requirement that motivates the use of Optically Pumped Magnetometers (OPMs).

In this work we present our development of an OPM and assess its suitability for magnetic anomaly navigation. We characterize the sensitivity and heading-error performance of the sensor and present preliminary results from a ground-vehicle field trial. We further discuss the feasibility of deploying such a system on moving platforms, including unmanned aerial vehicles, and identify the key technical challenges that remain on the path toward a practical, ruggedized system.

Title	Single probe beam tri-axial optically pumped magnetometer based on Voigt rotation in cells with gas buffer.
Authors	Ana Neves[1], Aryadine de Souza[1] and Hans Marin Florez[1] [1] Centro de Ciências Naturais e Humanas, Universidade Federal do ABC, Avenida dos Estados 5001, 09210-580 Santo André, São Paulo, Brazil

Optically pump magnetometers have changed the detection of weak magnetic fields in medical applications. This kind of sensor offers high sensitivity, high sample rate, low cost and it is cryogenic-free. Current developments of OPMs aim to increase the detection capacity, avoiding external interference in the signal detection. The single-axis OPM relies on detecting one particular frequency associated with the target magnetic field. Sensors that extract the tri-axial signals, can improve the source reconstruction, allow detection of external interference and eliminate movement artifact [1]. Extension of the single-axis sensor into a dual-axis or tri-axial sensors increases the number of modulating fields or pumping fields for each direction that is detected [2-4].

In this work, we show the implementation of the tri-axial technique in ref.[5], based on Voigt rotation, but now on a buffer gas vapor cell. Unlike the previous work, using paraffin coated cells which cannot be heated to increase the sensitivity of the magnetometer, now we demonstrate the implementation of the tri-axial technique with a vapor with buffer gas at 80°C. We show that by demodulating the first and second harmonic of the spin precession, the ellipticity of a single beam probe field, the sensor maps the three components of the magnetic field in one sensor i.e. the quadratures of the first harmonic maps the tilt in the transverse direction (x,z) and the second harmonic maps the longitudinal field in the y direction.

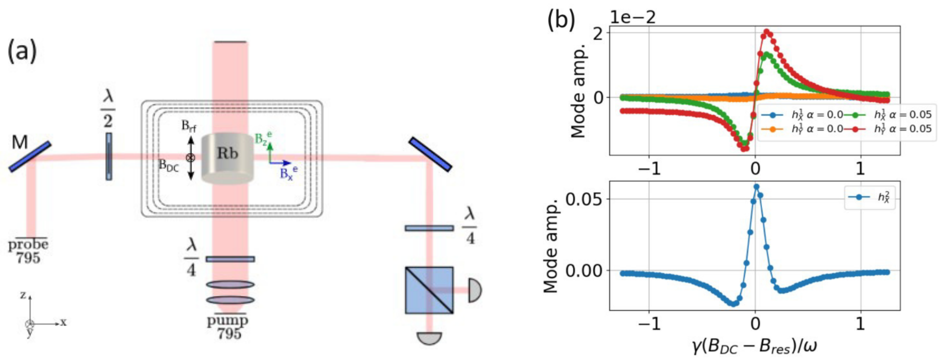

Figure 1: (a) Orthogonal pump probe configuration with circularly polarized pump and measure the ellipticity of the probe. (b) First ($h_{x,y}^1$) and second (h_x^2) harmonics of the probe field ellipticity. The applied tilted fields in z and x directions B_z^e, = α B_{DC} (green line) and B_x^e, = α B_{DC} (red line), respectively. The static field B_{DC} is along the y direction and measured at the FWHM of h_x^2 (blue line bottom plot).

This technique offers a single probe beam compact tri-axial detection scheme to implement OPM-MEG arrays systems with potential detection of external artifacts.

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[2] E. B. Alexandrov et al. , Meas. Sci. Technol 15, 918(2004).
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[4] Yeguang Yan et al. Opt. Express **30**, 18300-18309 (2022)
[5] Tadas Piragius et al, Phys. Rev. A 100, 023416 (2019).

Title	A Sensitive Dead-Zone-Free FID Vector Magnetometer
Authors	Jiang He[1], Xueke Wang[1], Huanghui Deng[1] and Dong Sheng[1] [1] University of Science and Technology of China, Hefei, China

The magnetometers based on free-induction-decay (FID) signals are mostly scalar ones. To extend its operation mode to a vector one, we adopt the scheme to add field pulses in three axes. The pulse field are driven by highly stable bipolar voltage-controlled current source on calibrated flexible printed circuit coils. To reach a high sensitivity and avoid the detection dead zones, we use the scheme of adding a reflecting mirror inside a multi pass-cavity-assisted cell as shown in Fig.1. Such a system is projected to reach 10 pT/√Hz on each axis with a pulse magnitude around 2000 nT in the geomagnetic field range. We will report the latest progress of this work.

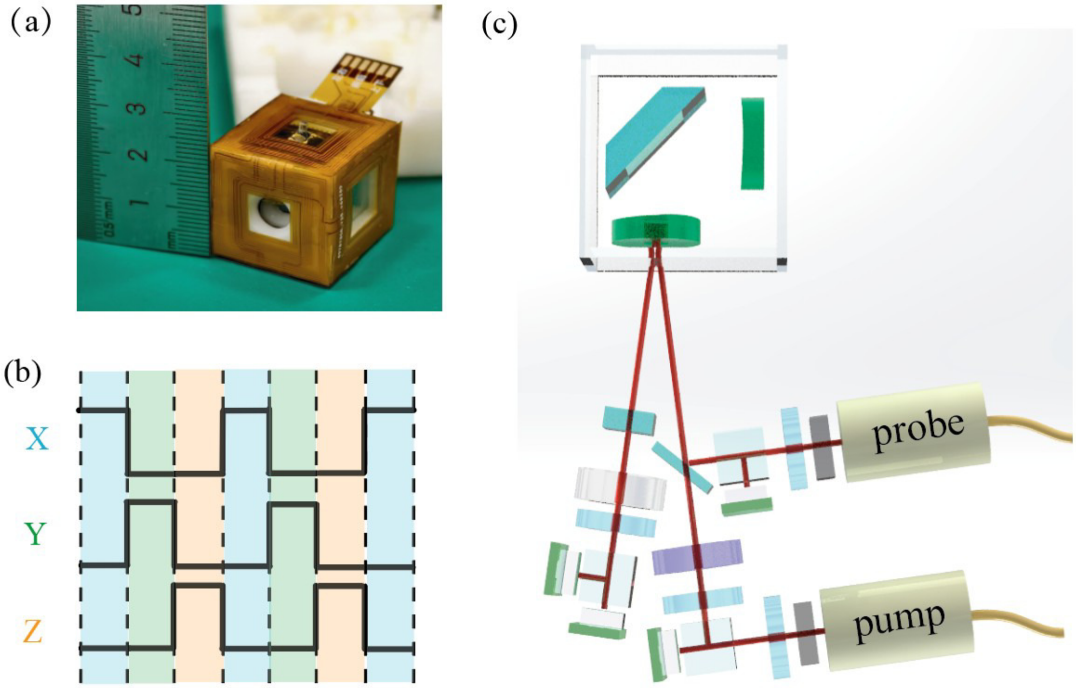

Figure 1: The vector atomic magnetometer setup.

Title	Omnidirectional Diamond-Based Vector Magnetometers
Authors	Xiaoyuan Zhang[1], Zhiyin Sun[1], Liyi Li[1] 1.School of Electrical Engineering and Automation, Harbin Institute of Technology, Harbin 150000, China

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 axes, or even unable to measure certain field directions. 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.

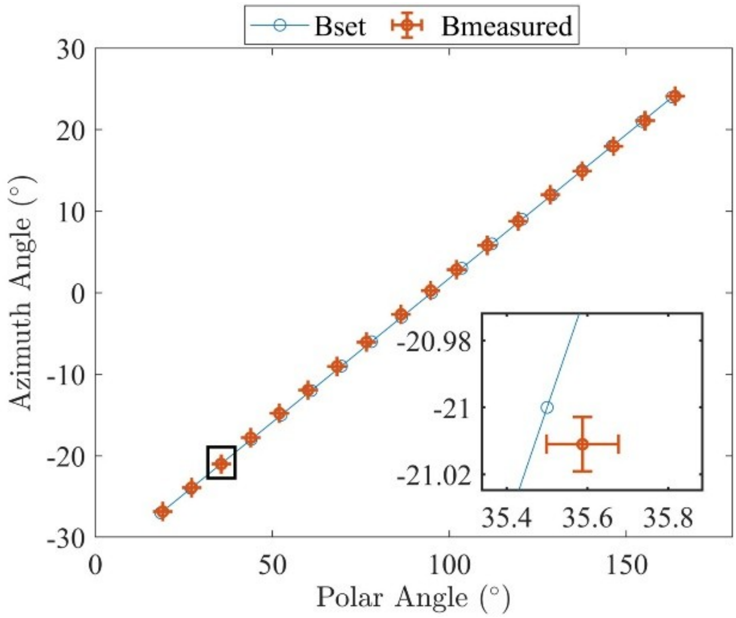

Figure 1. Comparison of set and measured directions of magnetic fields.

Title

Metrological Foundations for Benchmarking Optically Pumped Magnetometers

Authors

Eric Elzenheimer[1,2], Silvia Knappe-Grüneberg[2], Hartmut Matz[2], Jan Zerfowski[2,3], Surjo R. Soekadar[3], Michael Höft[1], Robert Rieger[1], Jens Voigt[2]

[1] Kiel University, Department of Electrical and Information Engineering, Kiel, Germany
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Over the past decade, SERF-OPMs have transitioned from complex tabletop laboratory prototypes to deployable multichannel MEG systems. However, meaningful cross-platform comparison remains hindered by inconsistent terminology and the absence of specification sheets across heterogeneous OPM implementations and manufacturers. Key quantities, such as sensitivity, gain, bandwidth, and noise, are applied inconsistently in literature or on manufacturer homepages, deviating from the International Vocabulary of Metrology. Furthermore, established definitions for highly-sensitive magnetometers are only partially used in practice [1], limiting reliable cross-system benchmarking and performance assessment, even for experts. This highlights the need for metrologically grounded foundations for OPM benchmarking to enable translation into biomagnetic applications while ensuring signal fidelity [2].

This talk establishes a metrologically consistent set of fundamental quantities and provides methodological guidance for the determination of key OPM benchmarking metrics. These include spectral noise density, detection of spurious spectral components (Fig. 1), quantification of inter-channel gain variations following dedicated sensor tuning (up to ± 10 %), and basic identification of cross-field responses. Comparative analysis of different commercially available multichannel OPM systems demonstrated effects not captured by conventional manufacturer specifications, underscoring the need for traceable, sensor and system-level benchmarking.

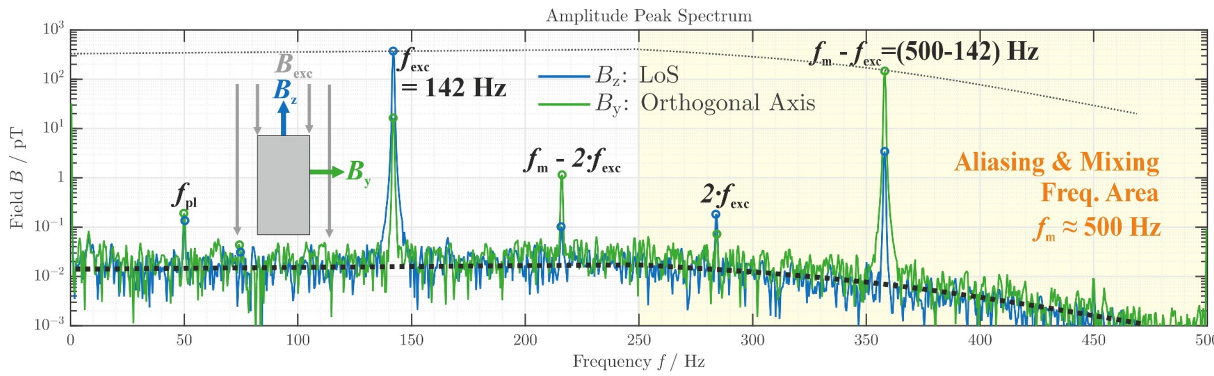


Figure 1: *Amplitude spectrum of an OPM system under sinusoidal excitation (dual-axis mode). Harmonics indicate nonlinear behavior, while aliasing and mixing products arising from insufficient anti-aliasing filtering, with some components falling within the measurement bandwidth.*

[1] E. Elzenheimer et al., *"Key Metrics and Experimental Test Bench for Assessing Highly Sensitive Magnetometers in Research"* in IEEE Sensors Journal, vol. 25, no. 2, pp. 2432-2455, Jan. 15, 2025, doi: 10.1109/JSEN.2024.3491164.

[2] E. Elzenheimer et al., *"Characterizing timing parameters in commercial SERF-OPM multichannel systems for biomagnetic field sensing"* in Measurement, vol. 263, p. 120140, 2026, doi: 10.1016/j.measurement.2025.120140.

Title	A Unified View of Sensitivity Limits in Magnetometry
Authors	Liwei Lei[1], Teng Wu[1], Hong Guo[1] [1] Beijing Key Laboratory of Quantum Sensing and Precision Measurement, and Center for Quantum Information Technology, and Institute of Quantum Electronics, Peking University, Beijing 100871, China

The sensing of a magnetic field with ultra-high sensitivity can be achieved using quantum magnetometers, which are based on the quantum natures of micro-particles. Unveiling the sensitivity limit of magnetometers is one of the central topics in quantum magnetometry [1]. In contrast to conventional quantum metrology, which usually treats the magnetic field as a classical parameter and therefore yields probe-dependent limits, a wide range of magnetometers across distinct technologies obey a probe-independent limit, known as the energy resolution limit [2-3]. As magnetometers approach and even challenge this limit, understanding its physical origin and its connection to probe-dependent limits becomes increasingly important.

In this presentation, we unify these limits within the framework of continuous linear measurement theory [4]. By treating the magnetic field as a quantum observable, we show that the energy resolution limit originates from the trade-off between measurement imprecision arising from quantum uncertainty in the sensor and backaction exerted on the field, providing a useful route for studying noise arising from the quantum nature of the signal itself. Our work establishes a bridge between different quantum noises in the information transfer of the sensing process, providing a unified picture for understanding the sensitivity limits in quantum sensing.

[1] L. Lei, T. Wu, and H. Guo, Natl. Sci. Rev. 12, nwaf129 (2025).

[2] M. W. Mitchell and S. Palacios Alvarez, Rev. Mod. Phys. 92, 021001 (2020).

[3] L. Lei, T. Wu, and H. Guo, Acta. Opt. Sin. 45, 2027008 (2025).

[4] A. A. Clerk, M. H. Devoret, S. M. Girvin, et al., Rev. Mod. Phys. 82, 1155 (2010).

Title	Floquet engineering of spin-spin interactions in a hybrid atomic system
Authors	Daniel Gavilan-Martin, Grzegorz Łukasiewicz, Vincent Kai Schäfer, Mikhail Padniuk , Adam Stefański, Adam Węglik, Emmanuel Klinger, Szymon Pustelny, Derek F. Jackson Kimball, Dmitry Budker and Arne Wickenbrock

We demonstrate dynamical control of the effective spin-spin interaction, dominated by Fermi-contact interaction, in a hybrid spin system via parametric modulation. We show that, in an alkali-metal-noble-gas comagnetometer, periodic modulation of the direction of the electron spin polarization with respect to the nuclear polarization leads to a Floquetinduced renormalization of the spin-exchange coupling, governed by a zeroth-order Bessel function. This effect enables continuous tuning and suppression of the effective interaction strength without altering the intrinsic properties of the system. We develop a theoretical model that supports the experimental measurements. The results establish a general mechanism for controlling interaction strengths in hybrid atomic systems and provide new opportunities for precision measurements and quantum memories.

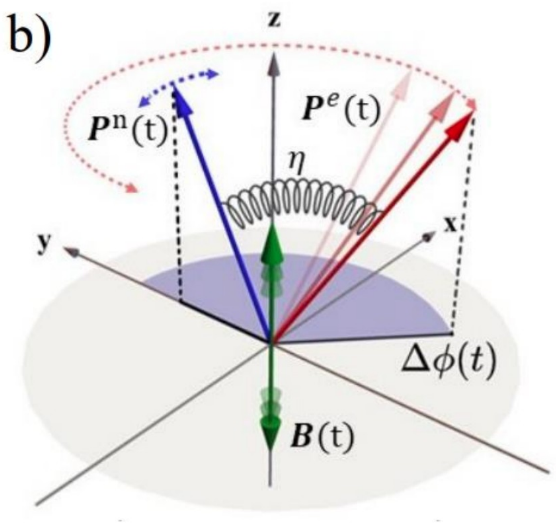


Figure 1: Sketch of the effect of the parametric modulation of the leading field in the interaction between electronic and nuclear spins. The modulated magnetic field (in green) causes both nuclear (Pn , in blue) and electronic (Pe , in red) polarization to precess in the transversal plane. The effect of the modulation for the nuclear spins is almost negligible, and the relative angle between polarizations can be changed. This affects the symmetrized coupling between them, which can be tuned via the amplitude and frequency of the modulation. [1] D. Gavilan-Martin, G. Łukasiewicz, arXiv:2604.18681

Title	Magnetic Resonance Line-width of Alkali-metal Atoms in Vapor Cells
Authors	**Nan Zhao**, Kezheng Yan, Jinbo Hu & Feng Tang Beijing Computational Science Research Center

The magnetic resonance linewidth of alkali-metal atoms under optical pumping is crucial for applications in atomic magnetometry. While the theoretical framework for this phenomenon has been fundamentally established over the past several decades, the escalating precision requirements of atomic magnetometers and comagnetometers necessitate a more rigorous understanding and precise calculation of the linewidth, revealing richer underlying physical mechanisms in the process.
To address this, we have systematically developed an analytical theory and a corresponding computational program for magnetic resonance based on the density matrix formalism. Specifically, we investigate the influence of varying magnetic field strengths on the magnetic resonance linewidth, providing an analytical treatment of the light-narrowing behavior[1]. Furthermore, we examine the effect of buffer gas pressure, detailing the linewidth behavior under conditions where the ground-state hyperfine splitting remains resolvable (i.e., when collisional broadening is comparable to the magnitude of the hyperfine splitting)[2]. Additionally, we explore the impacts of atomic diffusion within the vapor cell and boundary layer effects near the cell walls[3]. Our experimental observations based on these theoretical studies will be also discussed.
A profound quantitative understanding of these refined physical effects provides crucial support for experimental data analysis. Ultimately, the computational program developed herein will facilitate the optimization of optically pumped magnetometer (OPM) parameters and the advancement of novel designs and applications.
References:
1. Tang, F. & Zhao, N. Magnetic-resonance linewidth of alkali-metal vapor in the unresolved Zeeman-resonance regime. *Phys. Rev. A* **111**, 013103 (2025).
1. Yan, K., Hu, J. & Zhao, N. Optical pumping of alkali-metal vapor in the quasi-high-pressure regime. doi:https://doi.org/10.48550/arXiv.2603.05859.
Zhang, X., Hu, J., Xiao, D.-W. & Zhao, N. Frequency shift caused by nonuniform field and boundary relaxation in magnetic resonance and comagnetometers. *Commun Phys* **8**, 93 (2025).

Title	**Time-resolved MVPA decoding performance comparison between OPM-MEG and SQUID-MEG in a picture-naming task**
Authors	Itsuki Hamada[1], Kohei Fujisawa[2], Jion Tominaga[3], Yuki Ushijima[4], Rikuma Itabashi[4], Atsushi Shimojo[5], Hayato Watanabe[5,6], Koichi Yokosawa[5], Shinji Nishimoto[6,7], and Hiromu Sakai[8] [1] Graduate School of Advanced Science and Engineering, Waseda University, Tokyo, Japan; [2] School of Creative Science and Engineering, Waseda University, Tokyo, Japan; [3] Okinawa Institute of Science and Technology Graduate University, Okinawa, Japan; [4] Graduate School of Health Sciences, Hokkaido University, Sapporo, Japan; [5] Faculty of Health Sciences, Hokkaido University, Sapporo, Japan; [6] Center for Information and Neural Networks, NICT, Osaka, Japan; [7] Graduate School of Frontier Biosciences, University of Osaka, Osaka, Japan; [8] Faculty of Science and Engineering, Waseda University, Tokyo, Japan

Multivariate pattern analysis (MVPA) leverages the high temporal resolution of magnetoencephalography (MEG) to track the formation of neural representations over time. Optically pumped magnetometer (OPM) MEG places sensors closer to the scalp than conventional superconducting quantum interference device (SQUID) MEG, potentially yielding stronger signals, yet direct MVPA-based comparisons of the two systems remain scarce. We applied time-resolved MVPA to MEG signals recorded during an overt picture-naming task to determine when the OPM advantage emerges from visual input to speech production through lexical-semantic processing.

Using a between-subjects design, we recorded 8 participants with OPM (FieldLine HEDscan) and 16 with SQUID (Elekta Neuromag 360), collecting 1,500 trials of naming 25 object images per participant. After bandpass (0.1–80 Hz) and notch filtering, magnetometer data (OPM: 47 channels; SQUID: 102, randomly subsampled to 47) were epoched (−100 to 1,200 ms). For all 300 object pairs, sliding-window patterns (50 ms, 4 ms steps) were classified by SVM with 5-fold cross-validation, yielding time-resolved AUC. Significance was assessed via cluster-based permutation testing.

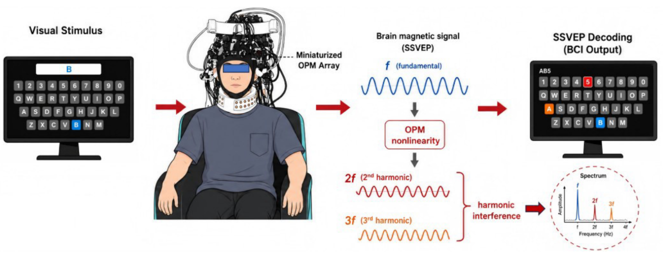
OPM outperformed SQUID throughout the epoch, peaking near 170 ms (AUC ≈ 0.73), with a pronounced, statistically significant divergence after 300 ms. Region-of-interest analyses showed comparable performance occipitally but a clear OPM advantage in temporal and frontal sensors. This pattern likely reflects the closer scalp coupling of OPM over lateral cortex, where the SQUID helmet fits less tightly. At matched channel counts, OPM thus provides a substantial decoding advantage, particularly for higher-order language processes engaging temporal and frontal cortices.

Title	Ghost Harmonics in OPM-Based SSVEP Brain–Computer Interfaces
Authors	Tengyue Long[1], Yaxiang Wang[2], Yan Dai[2], Lu Zhang[2] [1] Beihang University, Beijing, China [2] Hangzhou Lingci Medical Equipment Company, Hangzhou, China

Optically pumped magnetometers (OPMs) have emerged as a promising sensing technology for wearable magnetoencephalography and brain–computer interfaces (BCIs). In steady-state visual evoked potential (SSVEP)-based BCIs, frequency recognition depends on the reliable extraction of stimulus-related spectral components. However, OPMs operated under nonideal magnetic conditions may exhibit nonlinear responses caused by residual magnetic fields, imperfect field compensation, and intrinsic sensor nonlinearity. These effects can generate higher-order harmonic components that are not of neural origin. When such components overlap with SSVEP-related frequency features, they may introduce misleading spectral evidence and potentially reduce the robustness of frequency recognition. A schematic diagram is shown in Figure 1.

In this work, we define this sensor-level distortion as OPM-induced nonlinear harmonic error (ONHE) and analyze its potential impact on OPM-based SSVEP decoding. A theoretical error model is developed to describe the generation of second- and third-order harmonic components under residual magnetic fields and nonlinear OPM response characteristics. The relationship between residual field amplitude, input signal magnitude, sensor nonlinearity, and harmonic error strength is systematically analyzed. The results indicate that ONHE is a deterministic and frequency-selective error source, which may become particularly problematic when SSVEP command frequencies are harmonically related or when weak neural responses are measured in the presence of non-negligible residual fields.

At the same time, we propose the use of closed-loop control to suppress ONHE, which further underscores that closed-loop control is an indispensable technology for applying OPM arrays in SSVEP-BCI systems.



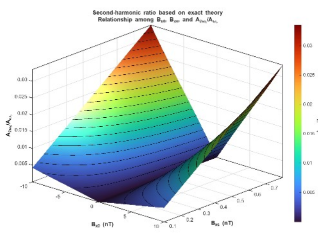


Figure 1 OPM-based SSVEP-BCI schematic diagram. Figure 2 ONHE simulation.

Title	Unshielded magnetoencephalography source imaging
Authors	Xiao Yang[1], Yicheng Wang[1], Teng Wu[1,2], and Hong Guo[1,2] [1] Beijing Key Laboratory of Quantum Sensing and Precision Measurement, and Center for Quantum Information Technology, and Institute of Quantum Electronics, Peking University, Beijing 100871, China [2] Beijing Laboratory of Biomedical Imaging, Beijing Municipal Education Commission, Beijing 100871, China

Magnetoencephalography source imaging (MSI) provides high spatiotemporal resolution for noninvasive brain mapping, but conventional MSI relies on magnetically shielded environments (SMSI). We propose an unshielded MSI (UMSI) approach using self-developed scalar optically pumped magnetometers operating in Earth's ambient field. Through numerical simulations, we systematically evaluate the effects of geomagnetic-field orientation and gradients on localization accuracy and compare performance with conventional shielded MSI. The results show that, under optimized conditions, unshielded MSI can achieve localization accuracy comparable to shielded systems, with potential advantages in spatial resolution. This work provides a theoretical basis for practical unshielded MSI.

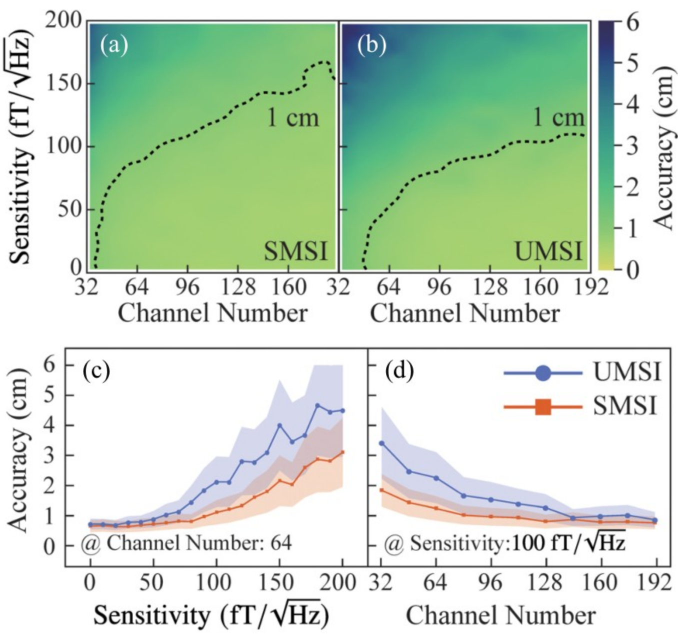


Figure 1: The effect of channel number and sensitivity on source-localization accuracy on UMSI and SMSI.

[1] Xiao Yang et. al., *Phys. Rev. Applied*, **25**, 034068 (2026).

Title	Observation of alignment tensor effects in metastability-exchange collisions with highly polarized 3He ensembles
Authors	Yida Sha[1], Kaiwen Yi[1], Xingqing Jin[1], Matteo Fadel[2], Xiang Peng[1] [1] Peking University, Beijing, China [2] ETH Zürich, Zürich, Switzerland

Highly polarized ^{3}He ensembles prepared by metastability-exchange optical pumping (MEOP) have been widely used in precision measurements and fundamental physics. Metastability-exchange (ME) collisions, serving as the basis of MEOP, are traditionally described in terms of atomic orientation, while the significant contributions of metastable alignment tensor at high polarization remain unexplored. In this work, we develop a linearized model under mean-field approximation to investigate alignment tensor effects in highly polarized ^{3}He, which originate from the metastable F = 3/2 manifold and are revealed through ME-induced relaxation and frequency shift. By means of free-induction-decay (FID) measurements, a pronounced dependence on nuclear polarization is experimentally observed in the response of the ground-state–metastable hybrid ^{3}He ensembles to the external magnetic field. Furthermore, after obtaining the characteristics of tensor-induced phenomena, we demonstrate good agreement between the experiment and the theory. This work advances the understanding of nuclear spin dynamics in highly polarized ^{3}He using MEOP. It further provides applications in systematic error correction of high-accuracy magnetometry, as well as in optimal protocol for the generation of nuclear spin-squeezed states. Besides the present work, we will also report other studies carried out by our group on the topic of long-lived ^{3}He nuclear spin squeezed states based on ME collisions, which could enable precision measurements beyond the standard quantum limit.

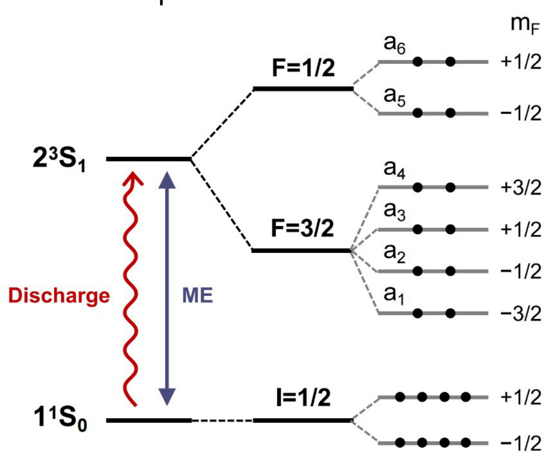


Figure 1: ^{3}He atomic energy-level diagram (not to scale).

Title	In-situ field compensation with high resolution for the SERF magnetometer
Authors	Yafen Cai, Deng Pan, Kun Yang, Xiangyan Kong Ningbo University, Ningbo, China

The spin-exchange relaxation-free (SERF) optically pumped magnetometer (OPM) is one of the most sensitive magnetic sensors, yet it needs to work in near-zero ambient magnetic fields. Triaxial magnetic field compensation is essential to achieve such a zero-field environment. Existing methods typically rely on complex and time-consuming iterative procedures to compensate for the environmental magnetic field. To address this problem, this article proposes an in situ magnetic compensation method that including two-stage: precompensation and precise compensation. The precompensation process eliminates most of the background magnetic field by reducing the fundamental frequency response of the SERF OPM. Subsequently, the precise compensation process further reduces residual magnetic fields through high-frequency magnetic field modulation. The long-term stability of the proposed compensation method was evaluated experimentally by monitoring the response of the SERF magnetometer with the compensation loop closed in the time domain within 25 min and calculating the corresponding Allan deviation. After compensation, the noise density of the OPM is about 20 fT/√Hz. To further improve the magnetic field compensation resolution of the system, spin polarization spatial uniformity in optically pumped atomic magnetometers will be improved with reflection scheme. Considering the emerging biomedical applications such as magnetocardiography (MCG) and magnetoencephalography (MEG), the arrays of the SERF OPMs is necessary. However, the magnetic field crosstalk between sensor unit is inevitable, we have investigated crosstalk reduction for magnetometer array by optimizing coil design.

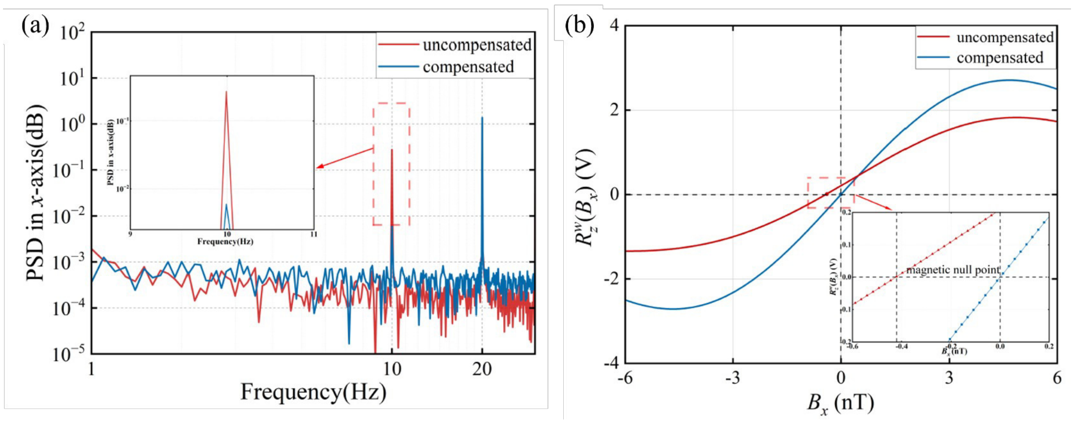


Figure 1: In-situ field compensation results. (a) Precompensation result; (b) Precise compensation result.

Title	OPM-Based Nondestructive Testing
Authors	Wenqiang Zheng[1,2], Kan Li[1,2], Shengran Su[2] [1] Zhejiang University of Technology, China [2] Mag-inspection Technology Co., Ltd., China

Quantum nondestructive testing (QNDT) based on atomic magnetometers has emerged as a promising approach for high-sensitivity detection of hidden defects in conductive and ferromagnetic structures. By exploiting the quantum spin response of alkali-metal atoms, atomic magnetometers can measure extremely weak magnetic fields induced by defects, corrosion, cracks, or eddy-current perturbations without damaging the tested object. In this talk, I will present recent progress in our group on using OPMs as nondestructive testing tools for complex industrial scenarios. Particular emphasis will be placed on the detection of abnormal weak magnetic fields and eddy-current signals generated by metallic defects, as well as the challenges and opportunities for translating quantum magnetic sensing technologies into practical NDT applications.

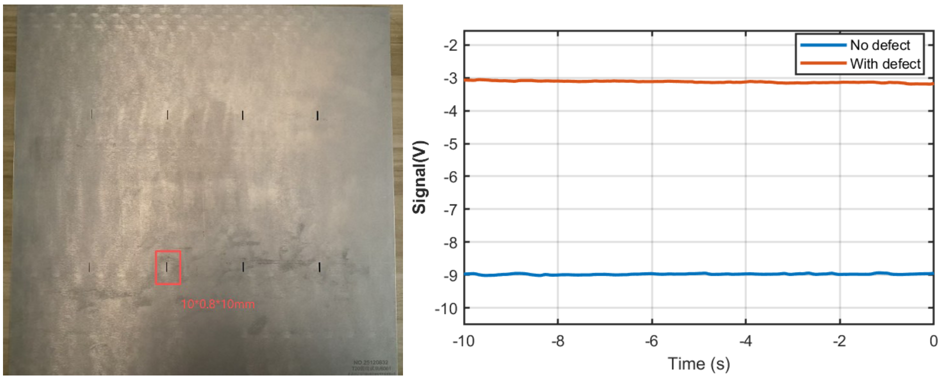


Figure 1: Quantum nondestructive testing of a crack sample using an atomic magnetometer. Left: photograph of the tested metallic sample containing a machined crack with dimensions of approximately 10 mm × 0.8 mm × 10 mm. Right: time-domain QNDT signals measured without signal averaging for the sample with and without the defect. A clear signal separation is observed, demonstrating the high signal-to-noise ratio of the QNDT response to the crack defect.

Title	A new method to measure the spin polarization of synchronous optical pumping
Authors	Chenlu Xu[1,2], Jiayu Jiang[1], Yangning Dai[1], Bin Zhang[1], Haifeng Dong[1] [1]School of Instrumentation and Optoelectronic Engineering, Beihang University, Beijing, 100191, China. [2]GNSS Center, Wuhan University, Wuhan 430072, China.

Optical synchronous pumping combined with free induction decay (FID) is an important method for scalar atomic magnetometry [1]. The initial polarization after optical synchronous pumping is a crucial parameter, directly affecting the amplitude of the measurement signal and serving as the basis for determining whether light narrowing can be achieved. Conventional polarization measurement methods require measuring the optical rotation angle, atomic density, absorption linewidth, laser detuning, and cell length to obtain the spin polarization. In this work, based on a steady-state model of pulsed pumping [2], we propose a new detection method that requires only the measurement of a single parameter—the optimal duty cycle—to determine the spin polarization. The effectiveness of this method is verified by comparison with the conventional approach. Figure 1 shows the relationship between the duty cycle and the resulting polarization, where k represents the pumping-relaxation ratio and different curves correspond to different optimal duty cycles. Therefore, by measuring the optimal duty cycle for optical synchronous pumping, the corresponding curve, along with the initial polarization of FID and the pumping-relaxation ratio, can be determined.

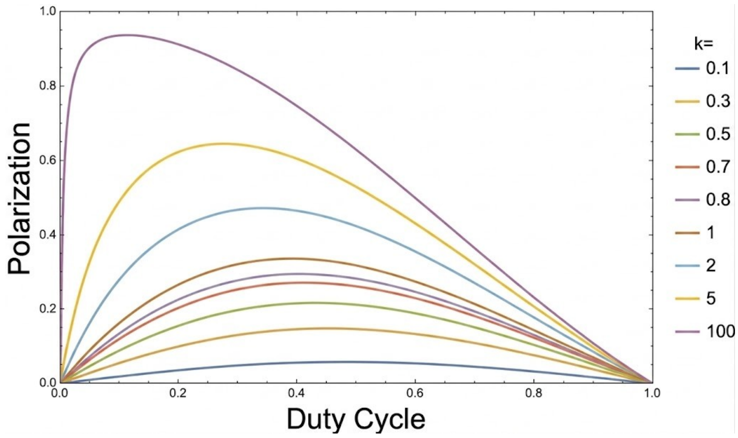


Figure 1: Relationship between the duty cycle and the polarization

[1] M. E. Limes, E. L. Foley, T. W. Kornack, S. Caliga, S. Mcbride, A. Braun, W. Lee, V. G., Lucivero and M. V. Romalis, Physical Review Applied, 2020, 14: 011002

[2] Mei Ling Wang, Meng Bing Wang, Gui Ying Zhang and Kai Feng Zhao,Chinese Physics B, 2016: 6

Title	Multi-frequency source localization accuracy of OPM-MEG versus SQUID-MEG
Authors	Wenyu Gu[1], Jingwei Sheng[1] 1 Quanmag Healthcare, Peking, China

Optically pumped magnetometers (OPMs) offer advantages for wearable, whole-head magnetoencephalography (MEG), but their bandwidth is typically narrower than that of superconducting quantum interference device (SQUID) sensors[1]. Because OPM frequency response can differ across channels even within the primary neural ban, OPM-MEG is often assumed to yield inferior dipole localization[2] owing to poorer inter-sensor spectral consistency. We evaluated this concern using a custom high-precision phantom. Dipole localization was performed at multiple frequencies from 1 to 80 Hz on a 96-site OPM-MEG system and a 102-site SQUID-MEG system. For both systems, localization error remained below 5 mm at every frequency, with mean errors near 2 mm. OPM-MEG and SQUID-MEG accuracies did not differ significantly across the tested band.
These findings indicate that present engineering and calibration practices can largely offset intrinsic bandwidth and response-shape differences between OPM and SQUID technologies, supporting comparable dipole localization performance in the 1–80 Hz band relevant to clinical and cognitive MEG.

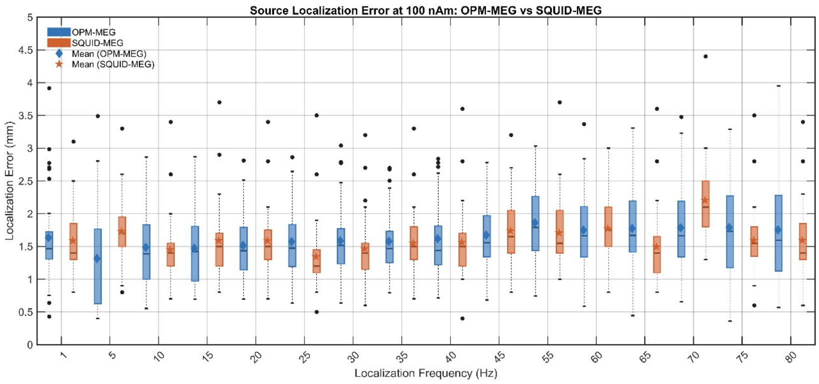


Figure 1 Localization error versus frequency for OPM-MEG and SQUID-MEG.

Reference :
[1] Osborne, J. et.al. SPIE, pp. 89–95. 2018
[2] Adachi, Y. et. al. IEEE Sens. J. 25, 41200–41208. 2025

Title	Individualized OPM-MEG helmets with active magnetic shielding for task-specific cortical source localization
Authors	A.M. Razorenova[a,b,d,#], A.B. Butorina[b], E.S. Skidchenko[b], D.A. Medvedeva[a,c], N.P. Fedosov[c], A.E. Ossadtchi[a], N.A. Koshev[a,b] [a] LLC "LIFT Center," Moscow, Russia [b] Skolkovo Institute of Science and Technology, Moscow, Russia. [c] Higher School of Economics, Moscow, Russia [d] MEG Center, Moscow State University of Psychology and Education, Moscow, Russia,

Wearable OPM-MEG enables magnetic sensors to be positioned close to the scalp and adapted to individual anatomy. This flexibility creates a coupled hardware and modeling problem: source localization depends on sensor placement, magnetic-field stabilization within the magnetically shielded room, sensor noise estimation, and the accuracy of the individual forward model. We present an integrated workflow for individualized OPM-MEG recordings aimed at task-specific cortical source localization.

Four participants were recorded with anatomically individualized helmets designed from individual head geometry. Recordings were performed over both hemispheres during auditory oddball stimulation. Measurements used active magnetic shielding based on a digital adaptive suppression system [1]. Reference magnetic-field measurements were used to drive compensation coils and suppress low-frequency residual-field fluctuations, maintaining the near-zero-field conditions required for stable OPM operation.

For each participant and hemisphere, sparse layouts were compared, including uniform layouts and layouts optimized for the stimulated cortical region using RALFE, a forward-model-based sensor selection algorithm [2]. The pipeline included OPM data conversion, event detection, bad-channel handling, sensor-noise estimation, individual forward modeling, and source localization.

Results show that individualized helmets combined with active magnetic shielding enable stable registration of auditory cortical responses in the target stimulation region. Source reconstructions were anatomically plausible and localized activity within the expected auditory cortical areas. Compared with uniform sparse layouts, RALFE-optimized layouts provided more consistent and focal localization across hemispheres and participants. These findings demonstrate that OPM-MEG performance depends on the co-design of helmet geometry, magnetic-field stabilization, and sensor-layout optimization. The proposed workflow provides a practical route toward reproducible, task-specific wearable MEG recordings with sparse OPM arrays.

[1] Skidchenko E., Butorina A., Fedosov N., Shevtsov O., Medvedeva D., Zhao D., Dubynin I., Fedorov M., Koshev N., Ossadtchi A. The Tale of Two Rooms: Comparison of QuSpin Zero-Field OPMs' Operation in Two Magnetically Shielded Environments. IEEE Transactions on Instrumentation and Measurement, 2025, Vol. 74, pp. 1–11. DOI: 10.1109/TIM.2025.3554317

Title	A Unified SERF-OPM System for Simultaneous MCG and MEG Measurements
Authors	Zihua Liang[1], Jialing Wang[1], Yaxiang Wang[2], Yan Dai[2], Lu Zhang[2] [1] Hangzhou Institute of Extremely-Weak Magnetic Field Major National Science and Technology Infrastructure, Hangzhou, China [2] Hangzhou Zero Magnetic Medical Equipment Co., Ltd., Hangzhou, China

Biomagnetic measurements offer a non-invasive window into cardiac and neural electrophysiological activity. However, magnetocardiography (MCG) and magnetoencephalography (MEG) are typically performed separately, limiting the ability to examine heart-brain interactions under a common physiological state, magnetic environment, and timing reference.

Here, we present a unified SERF-OPM system developed for MCG, MEG, and simultaneous MCG-MEG measurements. Unlike a simple co-location of two independent instruments, the system is built around shared magnetic shielding, stimulation, acquisition, and control architectures. In simultaneous mode, 64 sensor channels are used for cardiac measurements and 128 sensor channels for neural measurements; with dual-axis detection, the system supports up to 384 magnetic-field recording channels. Six acquisition controllers are synchronized by a phase-locked common clock and trigger, enabling microsecond-level timing alignment across the 192-channel system.

This system allows cardiac and neural magnetic signals to be recorded under the same experimental condition, providing a direct route to investigate the temporal relationship between cardiac dynamics, brain activity, and external stimulation. Potential applications include studies of heart-brain coupling, cardio-cerebral comorbidities, cardiac-related components in MEG data, and quantitative assessment of biomagnetic responses induced by interventions such as acupuncture.

Poster

BIOMAG 2026
23-25 Aug Beijing

wopm 2026
Workshop on Optically Pumped Magnetometers
Aug 21 (FRI) ~ 22 (SAT), 2026, BICC, BEIJING

Title	Evaluating the gradient tolerance in a single-axis optically pumped magnetometer
Authors	Syed Mohammad Suhaib[1], Samuel Lellouch[1,2], Michael Holynski[2] [1] School of Engineering, University of Birmingham, United Kingdom [2] School of Physics and Astronomy, University of Birmingham, United Kingdom

Optically Pumped Magnetometers (OPMs) are highly sensitive quantum sensors for weak magnetic field measurements. But their operation is noticeably affected by residual magnetic-field inhomogeneity. In practical environments, spatially varying magnetic field gradients exist across the vapour cell. In this research, we have built a Bloch-Torrey equations-based framework considering a single-axis Optically Pumped Magnetometer. This allows the spin polarisation to be investigated as it evolves under a position-dependent magnetic field across the vapour cell.

The applied magnetic field is swept across multiple fixed-gradient values, and the response curves are analysed in terms of signal amplitude, the curve's slope, and the deviation of its trajectory due to the gradients. It provides a systematic way to understand how magnetic field gradients affect the OPM's response. The framework offers a practical basis for evaluating gradient tolerance and spatial-field effects in single-axis OPM configurations.

Title: Femtosecond laser writing and welding of wafer-level all-glass vapor cells

Authors:
Prajal Chettri[1], Yasin Taheri Mazinani[2], Ruan Viljoen[1], Vincenzo Tamborra[1], Vito Giovanni Lucivero[1, 2, 3]
[1] QSENSATO Srl, Via Giovanni Amendola 173, 70126 Bari, Italy
[2] Dipartimento Interuniversitario di Fisica, Universita degli Studi di Bari Aldo Moro, 70126 Bari, Italy
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Alkali metal vapor cells are essential components of many quantum technologies, enabling highly sensitive electromagnetic field measurements and tests of fundamental physics. The growing demand for compact, deployable sensors is driving miniaturization. Wafer level fabrication offers a scalable and robust route to chip scale atomic devices, preserving long atomic coherence times and high optical quality while enabling integration with optical components [1]. Recently, femtosecond laser irradiation followed by chemical etching (FLICE) has emerged as a promising technique for fabricating three-dimensional, all glass, and laser-written vapor cells [2] suitable for applications such as optically pumped magnetometers, RF sensors, atomic clocks, and gyroscopes. In addition, a glass-to-glass laser welding technique combined with optical contact bonding has recently been introduced, demonstrating hermeticity and long-term stability of the fabricated cells [3].
In this work, we introduce a wafer level fabrication approach that combines FLICE with femtosecond laser glass welding, enabling the realization of millimeter-scale alkali vapor cells that are both three dimensionally structured and hermetically sealed entirely in glass. Following wafer dicing, individual cells are sealed using optical contact bonding supplemented by localized femtosecond laser spot welding. We demonstrate the functionality of the fabricated cells through absorption spectroscopy and single beam optical magnetometry.

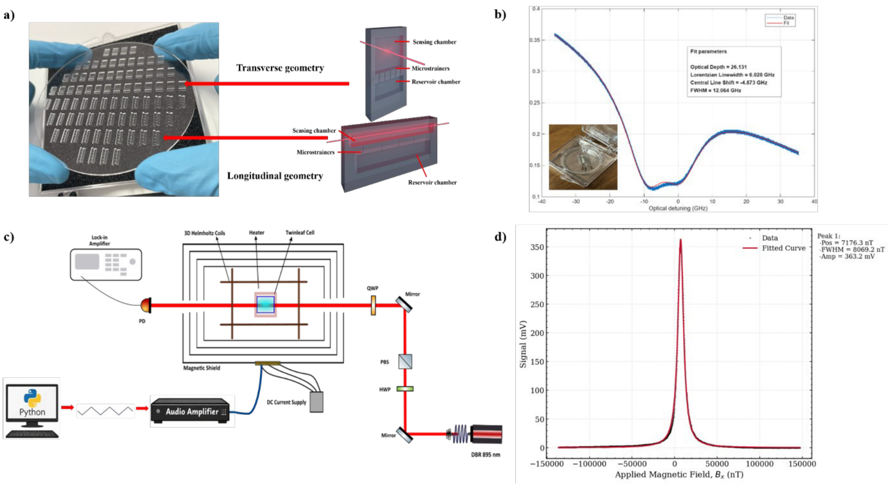


Figure 1: (a) FLICE-fabricated all-glass wafer showing two atomic vapor cell geometries (transverse and longitudinal). (b) Absorption spectrum (blue) and Voigt fit (red) with the cell at T = 80 ^{0}C. (c) Experimental schematic of single beam optical magnetometry. (d) Zero-field resonance magnetic field signal.

[1] D. G. Bopp, V. M. Maurice, and J. E. Kitching, ‘Wafer-level fabrication of alkali vapor cells using in-situ atomic deposition’, Journal ofPhysics: Photonics, vol. 3, no. 1, p. 015002, Jan. 2021
[2] V. G. Lucivero, A. Zanoni, G. Corrielli, R. Osellame, and M. W. Mitchell, ‘Laser-written vapor cells for chip-scale atomic sensing and spectroscopy’, Opt. Express, vol. 30, no. 15, p. 27149, Jul. 2022
[3] Nodop, D., Kügler, T., Wittkämper, F., Scholtes, T., Pester, S., Stolz, R., & Ruecker, J. Atomic vapor cells fabricated by femtosecond laser welding of standard-optical-quality glass.

Title	A Miniaturized Rydberg Atom Electrometer Enabled by On-chip MEMS Alkali Vapor Cell
Authors	Pan Chen[1,2], Yintao Ma[1,2*], Ju Guo[1,4], Yao Chen[1,2], Yanbin Wang[1,4], Mingzhi Yu[1,2], Ping Yang[1,4], Qijing Lin[1,2,3], Libo Zhao[1,2,3*] [1] State Key Laboratory for Manufacturing Systems Engineering, State Industry-Education Integration Center for Medical Innovations, International Joint Laboratory for Micro/Nano Manufacturing and Measurement Technologies, Shaanxi Innovation Center for Special Sensing and Testing Technology in Extreme Environments, Shaanxi Provincial University Engineering Research Center for Micro/Nano Acoustic Devices and Intelligent Systems, Xi'an Jiaotong University, Xi'an 710049, China [2] School of Instrument Science and Technology, Xi'an Jiaotong University, Xi'an 710049, China [3] Shandong Laboratory of Advanced Materials and Green Manufacturing at Yantai, Yantai 264000, China [4] School of Mechanical Engineering, Xi'an Jiaotong University, Xi'an 710049, China *corresponding authors (E-mails: yintaoma@xjtu.edu.cn and libozhao@xjtu.edu.cn)

Rydberg atoms, featured by the large electric dipole moment and exceptionally high polarizabilities, exhibit extreme sensitivity to external electric fields, making them ideal probe for high-precision, wideband microwave electrometry. The underlying sensing mechanism is primarily based on Electromagnetically Induced Transparency (EIT) and Autler-Townes (AT) splitting, with measurement results directly traceable to the International System of Units (SI). To overcome the limitations of traditional glass-blown vapor cells, such as poor consistency and low integration, this paper presents the chip-scale alkali-metal vapor cells developed using MEMS technology. The microfabricated vapor cells with a dual-chamber, glass-silicon-glass sandwich structure are designed and fabricated at wafer level. By utilizing the high anisotropy of inductively coupled plasma deep silicon etching, precise fabrication of high-aspect-ratio cavities is achieved. Furthermore, anodic bonding is adopted for vacuum packaging to ensure ultrahigh vacuum and low leakage rate. Meanwhile, the dual-channel differential detection optical system is constructed to effectively suppress common-mode noise arising from laser intensity fluctuations and environmental disturbances, and demonstrating a detection sensitivity of 10 $mV \cdot cm^{-1} \cdot Hz^{-1/2}$. This work not only advances the integration of Rydberg atom quantum sensors but also provides key technical support for future sub-wavelength microwave near-field imaging and the development of arrayed quantum sensing chips.

Suppression of Complex Environmental Magnetic Interference in Open Magnetocardiography (MCG) Based on OPM Sensors

Yunyang Lian, Yimeng Zhai, Wenkai Luo, Hongyu Wang, Luzhang*

The open magnetocardiography (MCG) imaging system based on an optically pumped magnetometer (OPM) offers excellent application prospects for the early screening and diagnosis of cardiac diseases due to its cryogen-free operation, high sensitivity, non-invasiveness, lack of radiation, high efficiency, fast speed, and low cost.
However, compared to traditional closed systems operating in expensive magnetically shielded environments, low-cost open MCG devices are more susceptible to complex ambient background magnetic field disturbances. Theseprimarily include complex magnetic field interferences present in hospital settings, such as those from MRI machines, CT scanners, elevators, and high-power electrical equipment. Such disturbances can lead to OPM operating point shifts, reduced sensitivity, and decreased accuracy in MCG signal measurement.To address the problem of complex environmental magnetic field interference faced by open MCG imaging devices, this paper proposes an active magnetic compensation scheme based on OPM sensors. This scheme employs a multi-stage, synergistic approach combining bucket-opening gradient compensation with working-area shim compensation.

Through a systematic analysis of the spatial distribution characteristics of the magnetic field in the open MCGdevice, a synergistic compensation structure using a bucket-opening gradient coil and shim coils is proposed. Specifically, the bucket-opening gradient coil suppresses the magnetic field gradient components inside the bore, achieving gradient uniformity within the working area. The shim coils further compensate for residual uniform magnetic fields, enabling fine adjustment of the local magnetic field environment. To minimize the impact of the compensation system on MCG signal acquisition, OPM magnetic field sensors are placed in regions insensitive to the target signal, thereby avoiding compensation of the desired MCG signals. These sensors sense environmental interference magnetic field changes in real-time and establish a feedback loop. Regarding the control strategy, to address the coexistence of DC/low-frequency disturbances and specific frequency interferences in the ambient magnetic field, a composite control algorithm combining Proportion-Integration-Differentiation (PID) control and Proportional-Resonant (PR) control is employed. This approach achieves fast compensation of low-frequency varying components and high-gain tracking and suppression of specific frequency interferences, thereby enhancing the system's dynamic capability to suppress complex environmental disturbances.

This system effectively reduces interfering magnetic fields in open MCG imaging devices and improves the signal-to-noise ratio (SNR) of MCG signals measured by the OPM. The system has been successfully deployed in 11 hospitals. Taking Hospital XX as an example, the maximum environmental magnetic noise in the measurement plane of the MCG probe was compensated from 250 fT/√Hz @ 1-40 Hz down to 50 fT/√Hz @ 1-40 Hz, achieving an 18-fold suppression of magnetic noise at 1 Hz.

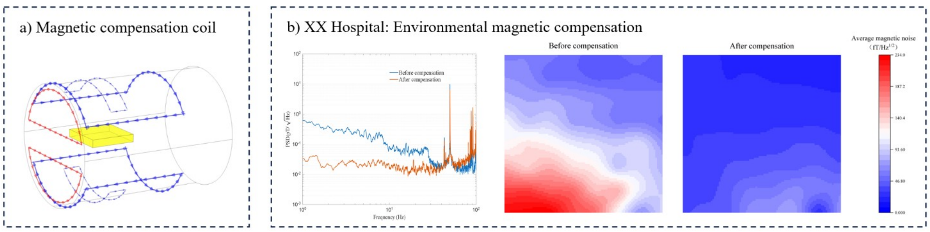


Figure 1. a) Schematic diagram of the magnetic compensation coil. b) Average magnetic noise in the working area before and after magnetic compensation at XX Hospital

Title	Small Atomic Magnetometer Based on Modular Concept
Authors	Yangning Dai[1], Chenlu Xu[1] [1] Beihang University, Beijing, China

Atomic magnetometers frequently measure the differential Faraday rotation angle of a split light beam to characterize the target magnetic field. Conventional magnetometers adopt monolithic integrated designs, with all functional modules enclosed in one unified mechanical frame. This configuration renders modules non-interchangeable and prevents independent performance optimization, which severely restricts equipment reusability. To address this issue, when designing a compact magnetometer, we divided it into two modules: a vapor cell module and a polarimetric detection module. The vapor cell module integrates a heating element and electromagnetic coils. Its coils are patterned onto Printed Circuit Boards covering all six faces of the module, and the entire assembly measures 20×20×20 mm³. The polarimetric detection module consists of a polarization beam splitter, two photodetectors and a transimpedance amplifier circuit, with identical overall dimensions of 20×20×20 mm³. The pins of the heating element, coils, and transimpedance amplifier are all routed via connectors to a 69×68 mm² motherboard at the bottom, with the right side of the motherboard providing interfaces for external signals, as shown in Figure 1. This design allows any module to be easily 'plugged and unplugged' from the motherboard when replacement is needed, thereby enabling open-source use and enhancing the reusability of the various modules of the atomic magnetometer.

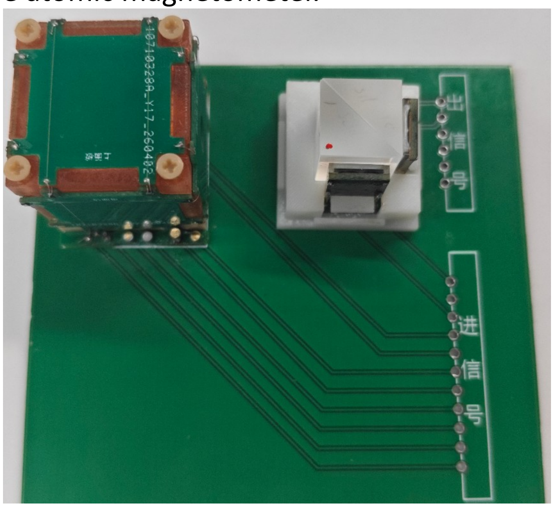


Figure 1: Overall Assembly Diagram of Small Modular Magnetometer

[1] ALLRED J C, LYMAN R N, KORNACK T W, et al. High-Sensitivity Atomic Magnetometer Unaffected by Spin-Exchange Relaxation[J]. Physical Review Letters, 2002, 89(13): 130801.

Title	Non-Contact Detection of Third-Harmonic Magnetic Fields from Insulators Using an FID Atomic Gradiometer
Authors	Wei Gao[1], Huanghui Deng[1],Haoyu Liu[1] , Xueke Wang[1], Jiang He[1], Kai Liu[1], Bin Miao[1], Dong Sheng[1], Yuming Wang[1] University of Science and Technology of China, Hefei, China[1]

The aging of high-voltage AC insulators can induce nonlinear leakage-current harmonics, in which the 150 Hz third harmonic of the 50 Hz power frequency may serve as a diagnostic signature.In this work, a first-order gradiometer system is used for on-site detection of third-harmonic magnetic fields from insulators. This system consists of two closed-loop FID atomic magnetometers: one placed near the insulator to measure local magnetic fields, and the other positioned farther away to monitor background fields. Differential processing will suppress power-frequency interference and environmental common-mode noise. The experiment was carried out in an ultra-high-voltage laboratory environment. A 50 Hz high-voltage AC excitation was applied to test insulators, and the magnetic response near the insulator was measured without electrical contact with the high-voltage circuit. Particular attention was paid to the spectral component around 150 Hz, corresponding to the third harmonic of the power frequency. The results show that the FID atomic gradiometer can capture weak harmonic magnetic signatures under high-voltage AC conditions, demonstrating the feasibility of using atomic magnetic sensing for non-contact detection of insulator-related third-harmonic signals. Compared with conventional contact-based current measurement methods, the proposed approach offers inherent electrical isolation and improved operational safety, providing an experimental basis for further investigation of the relationship among insulator aging, nonlinear leakage-current harmonics, and measurable magnetic-field signatures.

H. Ahmad, Journal of Electrostatics 66, 156 (2008).

Title	Polarization-gradient optical pumping in an atomic magnetometer
Authors	XiaonaLiu[1], YujieSun[1,*], ZhaoyingWang[1,2,*] [1]Zhejiang Key Laboratory of Micro-Nano Quantum Chips and Quantum Control, School of Physics, Zhejiang University, Hangzhou 310027, China [2]State Key Laboratory of Ocean Sensing, ZJU-Hangzhou Global Scientific and Technological Innovation Center, ZhejiangUniversity,Hangzhou311215,China

Dead zones limit Mz/Mx optically pumped magnetometers when the light–atom interaction vanishes for specific magnetic-field directions. We demonstrate a polarization-gradient optical-pumping scheme using counter-propagating lin⊥lin beams in an RF-driven ^{87}Rb atomic magnetometer. The longitudinally varying polarization field allows thermal atoms to sample a periodic sequence of linear and circular polarizations, producing an effective spatially averaged atomic state. Compared with single-linearly polarized pumping, the lin⊥lin configuration suppresses dead zones in the transverse plane of probe-beam propagation: the normalized absorption signal remains nonzero over 0°–180°, with a minimum of about 40% of the maximum amplitude. In the longitudinal plane, two non-canonical magic-angle-like minima appear near 30° and 150°. These results are explained by a multipole-moment model based on an effective spatially averaged density matrix. This scheme provides a simple route to extending the angular response of compact atomic magnetometers.

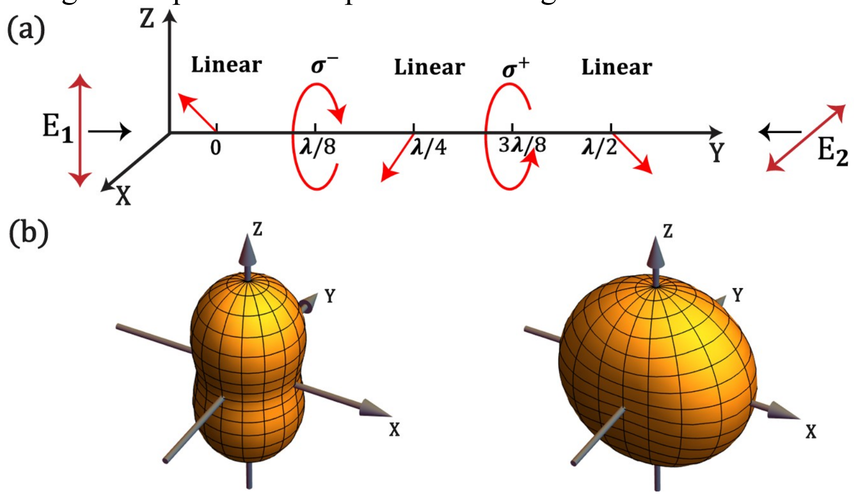


Figure 1: (a) The total polarization generated by the lin⊥lin scheme, which exhibits a periodic sequence of linear and circular polarizations with period $\lambda/2$. (b) The AMPS of the atomic ensemble under single linearly polarized pumping E1(left) and the overall equivalent AMPS under lin⊥lin pumping(right) with in one spatial cycle.

Title	The Bell-Bloom-type optically-pumped FID Rubidium atomic magnetometer with a multi-passing probe beam and two counter propagating pump beams
Authors	Yongbiao Yang[1], Zhengyu Su[1], Yang Li[1], Yanhua Wang[1], Jun He[1], Xiaojun Jia[1], Junmin Wang[1] [1] Shanxi University, Shanxi Provnice, China
Abstract	The Bell-Bloom-type optically-pumped atomic magnetometers are well-suited for weak geomagnetic field detection. However, conventional single-beam pumping introduces an atomic spin polarization gradient, which limits measurement accuracy and sensitivity. To address this issue, we propose and experimentally demonstrate a Bell-Bloom-type rubidium FID magnetometer using orthogonally polarized counter-propagating pumping and multi-pass probe detection. This scheme homogenizes atomic spin polarization, suppresses light shifts and power broadening, and the five-pass probe configuration significantly enhances signal amplitude. Experimental results show that compared with the traditional scheme, the proposed magnetometer greatly improves magnetic field measurement accuracy, with sensitivity improved from 18.9 pT/√Hz to 3.1 pT/√Hz. This work provides an effective approach for optimizing atomic magnetometer performance and extending its applications to geomagnetic monitoring, geophysical exploration, archaeological prospecting.

Title	Operation of commercial SERF zero-field OPM in an unshielded environment
Authors	Seong-min Hwang[1] and Jeong Hyun Shim[1] [1] Korea Research Institute for Standards and Science, Republic of Korea

SERF zero-field OPMs are used exclusively in magnetically shielded environment with high shielding factor due to their operating principle that requires an absolute magnetic field free condition on the metal vapor cell. This requirement leads to limited working ranges of magnetic field for the zero-field OPMs. For example, QuSpin specifies working range of its QZFM OPMs as ±50 nT.

We demonstrate a commercial SERF zero-field OPM (QuSpin QZFM gen. 3 triaxial) operation in an unshielded environment without any magnetic shields nor any reference magnetic sensor other than the zero-field OPM itself.

A simple proof-of-concept setup consisting of a 3-axis Helmholtz coil and an analog PID controller (SRS SIM960) allowed rough manual field-zeroing process where the ambient magnetic field was brought down to within working range of QZFM, which allowed automatic field-zeroing and calibration of the sensor as provided by the manufacturer, with the PID controller reducing line noise level to within dynamic range of the sensor.

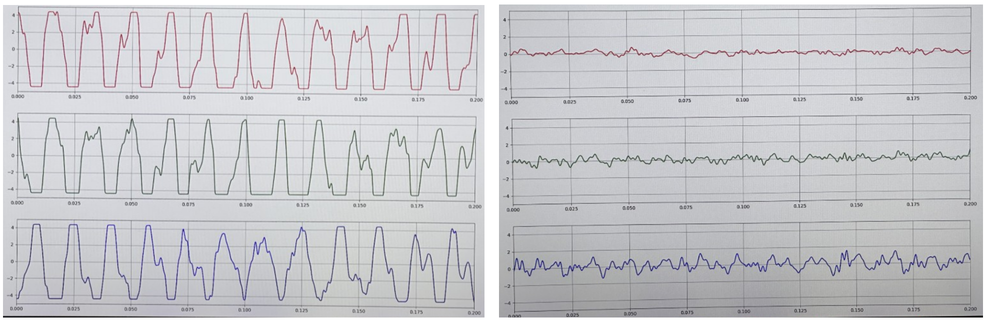


Figure 1: Analog outputs from SERF zero-field OPM in unshielded environment. Left: As-is (calibration fails), Right: With PID feedback (calibration OK)

By combining PID output and OPM output as the final sensor value, a SERF zero-field OPM operating in unshielded environment, resilient to Earth-field, is possible.

This research was supported by the Challengeable Future Defense Technology Research and Development Program through the Agency For Defense Development(ADD) funded by the Defense Acquisition Program Administration (DAPA) in 2025 (No. 915122101)

Title	Adaptive Real-Time Magnetic Field Tracking beyond Prior Waveform Constraints
Authors	Yihan Wang[1], Xiaofeng Jin[1], Yuchuan Ming[1], Jianxiang Miao[1], Xiao-Ming Lu[1], M. W. Mitchell[2], and Jia Kong[1] [1]Hangzhou Dianzi University, Hangzhou, China [2]The Barcelona Institute of Science and Technology, Barcelona, Spain

We demonstrate a parameterestimation framework based on the adaptive extended Kalman filter for dynamic magnetic-field estimation in quantum systems using spin-noise measurements—a challenging regime characterized by weak signals. By modeling the magnetic field as an unknown parameter, the proposed approach alleviates model dependence in state estimation. Furthermore, by introducing an adaptive algorithm with real-time noise estimation, our method overcomes the measurement noise intensity constraints of conventional extended Kalman filtering and enhances its practical applicability.

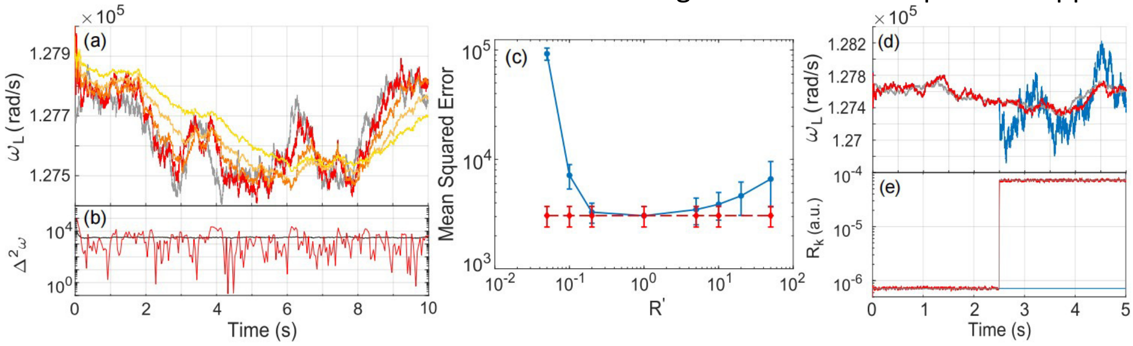


Figure 1: (a) True value of Larmor frequency, adaptive extended Kalman filtering(AEKF), and extended Kalman filtering(EKF) tracking results with different given measurement noises. (b) Squared instantaneous estimation error and the variance estimated by the AEKF. (c) Mean squared error as a function of the estimation performance used in the EKF and AEKF. Larmor frequency estimation (d) and adaptive measurement-noise identification (e) under environmental interference.

Title	Generation of Magnetic Frequency Comb via Pulse Feedback Rb-Xe Spin Maser
Authors	Qingchang Li[1,2,3], Weiyu Wang[1,2,3], Erwei Li and Guobin Liu[1,2,3,*] [1]National Time Service Center, Chinese Academy of Sciences, Xi'an 710600, China [2]Key Laboratory of Time Reference and Applications, Chinese Academy of Sciences, Xi'an 710600, China [3]University of Chinese Academy of Sciences, Beijing 100049, China * Email: liuguobin@ntsc.ac.cn

Spin maser is a powerful tool for precision measurement of magnetic field and widely used in fundamental physics and practical applications [1,2,3]. Here we realize a magnetic frequency comb based on a pulse feedback Rb-Xe spin maser [4]. Unlike traditional continuous feedback spin maser, the detected spin signal is modulated by a square wave sequence. These pulses are subsequently amplified and applied back to the atomic vapor cell as a feedback magnetic field, as shown in Figure. 1(a).

When the spin Larmor precession in the time domain is modulated by a pulse with duration , its frequency-domain response is equivalent to the convolution of the Larmor signal and the square-wave function. As shown in Figure. 1(b), this periodic perturbation induces symmetrically distributed discrete sidebands on both sides of the original Larmor frequency, with the frequency spacing equal to the repetition frequency of the feedback pulses. The magnetic frequency comb at low magnetic field may overcome the bandwidth limitation of conventional continuous feedback spin maser and provides an efficient detection platform for precision magnetic measurements and broadband searching for spin-dependent new physics.

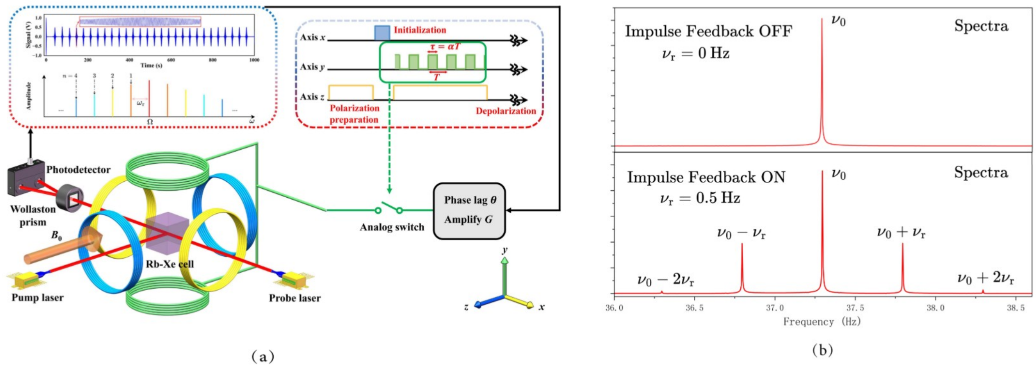
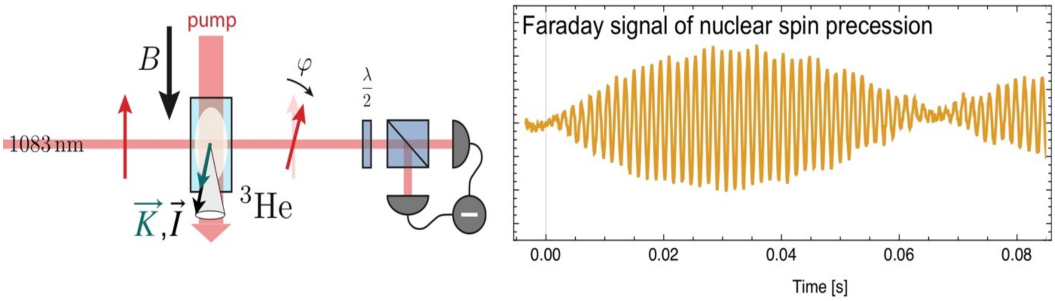


Figure. 1: (a) Experimental setup (b) Spectra of the pulse feedback spin maser versus continuous spin maser.

[1] M. Rosenberry and T. Chupp Atomic Electric Dipole Moment Measurement Using Spin Exchange Pumped Masers of 129Xe and 3He. Phys. Rev. Lett. 86, 22-25(2001)
[2] M. Jiang, H. Su, Z. Wu, X. Peng, D. Budker. Floquet maser. Sci. Adv. 7:eabe0719(2021)
[3] P. Bevington, R. Gartman, and W. Chalupczak, Alkali-metal spin maser for non-destructive tests Appl. Phys. Lett. 115, 173502 (2019)
[4] Feng, M., Wu, L. & Liu, G. Nonlinear dynamics in an artificial feedback spin maser. *Phys. Rev. A* 111, 023118 (2025)

Aug 21 (FRI) ~ 22 (SAT), 2026, BICC, BEIJING

Title	Towards optical quantum control of nuclear spins in a Helium-3 gas
Authors	M. H. Saeed[1], M. Fadel[2], A. Serafin[3], G. Tastevin[3], P.J. Nacher[3], A. Sinatra[3], and P. Treutlein[1] 1. Department of Physics, University of Basel, Switzerland 2. Department of Physics, ETH Zurich, Switzerland 3. Laboratoire Kastler Brossel, ENS Paris, France
Abstract	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].  Figure 1: Optical Faraday measurement of Helium-3 nuclear spin Rabi oscillations [1] A. Serafin, M. Fadel, P. Treutlein, and A. Sinatra, Phys. Rev. Lett. 127, 013601 (2021). [2] A. Serafin, Y. Castin, M. Fadel, P. Treutlein, and A. Sinatra, Comptes Rendus Physique 22, 1 (2021).

Title	Development and Performance Evaluation of MEMS Bi-planar Coils for Integrated Chip-Scale Atomic Magnetometers
Authors	Yanjie Zhang[a], Jiyang Wang[a], Ruyang Guo[a],Yanbin Wang[a],Yao Chen[a,*] [a] School of Instrument Science and Technology, Xi′an Jiaotong University, Xi′an, 710049, China *yaochen@xjtu.edu.cn
Abstract	Magnetic compensation coils are critical components for maintaining the near-zero field environment required by Spin-Exchange Relaxation-Free (SERF) atomic magnetometers. However, traditional coils are bulky and difficult to integrate. This paper proposes a chip-scale solution using MEMS bi-planar coils, which significantly reduces the sensor probe's volume and integration complexity. To overcome the integration bottlenecks of traditional macroscopic coils, a 3D bi-planar configuration was optimized using finite element analysis (FEA). A dual-layer counter-current wiring scheme was implemented to suppress lead-wire interference and enhance field uniformity. The coils, measuring 10 mm × 8.5 mm, were fabricated on silicon substrates using micro-nanofabrication processes, including DC magnetron sputtering and ICP etching for electrical vias. The performance was characterized in-situ within a compact opto-mechatronic SERF probe (12 mm × 15 mm × 43 mm). By monitoring ^{131}Xe nuclear spin precession, the coil constants were calibrated at 68.22 nT/mA for the x/y-axes and 395.98 nT/mA for the z-axis. Experimental results demonstrate high magnetic field uniformity within a 2 mm^3 central volume, with a gradient-induced error of 0.09±0.02. These results validate the feasibility of the proposed MEMS bi-planar coils for high-performance, integrated quantum sensing applications.

Title	A low-cost method to reduce residual DC magnetic field in a magnetically shielded room using dry cells
Authors	Yoshiaki Adachi[1], Shigenori Kawabata[2], Takanori Kato[3] [1]Kanazawa Institute of Technology, Ishikawa, Japan [2]Institute of Science Tokyo, Tokyo, Japan [3]Sumitomo Heavy Industry, Tokyo, Japan

In recent years, the performance of Optically Pumping Magnetometers (OPMs) has improved significantly, and particularly Spin-Exchange Relaxation-Free (SERF) type OPMs have emerged as magnetic sensors with magnetic field sensitivity approaching that of Superconducting Quantum Interference Devices (SQUIDs), leading to increasing applications in biomagnetic measurements. Some research sites are even considering replacing existing SQUID-based biomagnetic measurement system with OPM-based systems. However, OPMs generally impose stricter requirements on magnetic shielded rooms (MSRs) than SQUIDs, which can become a barrier to OPM deployment.

In particular, SQUIDs exhibit periodic flux-voltage characteristics, and gradiometer can be constructed through appropriate pickup coil designs. Therefore, the requirements on the DC residual magnetic field inside the MSR are relatively relaxed. In contrast, SERF-type OPMs require a near-zero magnetic field environment for operation. Consequently, when the DC residual magnetic field is large, compensation by the cancellation coils integrated into individual OPMs may become insufficient, resulting in unstable operation.

In this presentation, we propose a relatively low-cost method for reducing DC residual magnetic fields in existing magnetic shielded rooms with large residual fields by using multicore cables and dry cells, thereby enabling biomagnetic measurements with OPMs.

Using dry cells as the power source inside the MSR allows the entire circuit to be self-contained within the shielded environment, thereby eliminating the risk of noise being conducted into the room through cables connected to external equipment. In addition, unlike commercially available mobile battery packs, dry cells do not contain clock-driven control ICs or switching power supply circuits that can act as sources of electromagnetic noise. For these reasons, dry cells provide a low-cost, low-noise power solution, making them well suited for this application.

By applying this method, we reduced the DC residual magnetic field inside the existing MSR at Institute of Science Tokyo from approximately 160 nT to below 80 nT, and successfully performed magnetocardiography measurements using OPMs in the MSR.

Title	Compact Mz Atomic Magnetometer and Its Applications in Biomagnetic Signals Measurement
Authors	Chuangzhen Guo, Kun Yang, Chenghui Zhen, Yafen Cai and Xiangyan Kong[1] Ningbo University, Ningbo, China
Abstract	Magnetocardiography (MCG) measures the weak magnetic fields generated by the myocardial electrical current of the heart, providing an important non-invasive tool for the early diagnosis and functional assessment of cardiovascular diseases. However, existing high-sensitivity MCG systems based on zero-field atomic magnetometers typically operate in well-shielded environments (~50 nT), which limits their feasibility for bedside clinical monitoring and portable applications. In this work, we developed a compact Mz-mode total-field atomic magnetometer for MCG measurements, where a chip-scale vertical-cavity surface-emitting laser (VCSEL) serves simultaneously as the pump and probe light source. Several key parameters have been systematically optimized, including optical power density, cell temperature, and radio-frequency field. As a result, the magnetometer achieved a magnetic field sensitivity of 0.8 pT/√Hz under a background magnetic field of approximately 5 μT. Furthermore, we tested the response of the homemade magnetometer to both coil-simulated and human MCG signals, and successfully captured characteristic MCG features, including P waves, QRS complexes, and T waves. In addition, after multi-cycle averaging, the signals measured by the Mz magnetometer were compared with single-cycle MCG signals obtained using a zero-field magnetometer, yielding a Pearson correlation coefficient of r = 0.99. These results demonstrate that the developed compact Mz-mode atomic magnetometer provides a promising solution for future portable MCG systems.

Title	Neural Network Enhanced Extraction of Fetal Magnetocardiography from Single-Channel Noncontact Recordings
Authors	Ziyan Zhou, Kun Yang, Yafen Cai, Yu Xin and Xiangyan Kong Ningbo University, Ningbo, China

Noninvasive fetal cardiac monitoring is critical for detecting congenital heart defects (CHD) and reducing perinatal mortality[1]. Fetal magnetocardiography (fMCG) offers higher spatiotemporal resolution than fetal electrocardiography (fECG), but it is severely contaminated by maternal interference[2]-[4]. To address this issue, we proposed the spatial-temporal convolutional neural network and bidirectional long short-term memory (STCNN-BiLSTM) model, a hybrid morphological and temporal feature-fusion network for single-channel fMCG extraction. The model employs small-kernel 1D convolutions (kernel size of 5) to extract short-term morphological transients and Bi-LSTM units to capture long-range rhythmic dependencies. To accurately reconstruct the fMCG, a composite loss combining mean squared error (MSE) with a high-weight Pearson correlation coefficient (PCC) is employed to reduce MSE-induced distortion and preserve clinical features such as P and T waves.

The proposed model was validated on a multi-source dataset constructed from clinical abdominal fetal ECG, synthetic signals, and OPM-based simulated human and mouse MCG recordings, yielding a mean PCC of 0.9819 for reconstructed waveforms and an F1-score of 97.0% for fetal QRS (fQRS) detection. Moreover, amplitude spectrum analysis further corroborates the effectiveness of the proposed model in fMCG extraction. This research provides a robust and high-fidelity solution for fMCG extraction, demonstrating strong potential for clinical translation

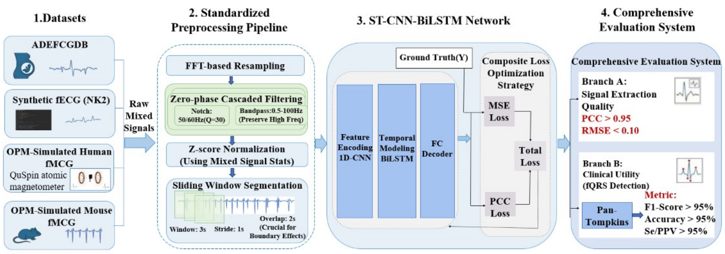


Figure 1: Block diagram of the proposed ST-CNN-BiLSTM for single-channel fMCG extraction.

[1] C. W. Tsao, A. W. Aday, Z. I. Almarzooq, A. Alonso, A. Z. Beaton, et al., “Heart disease and stroke statistics—2022 update: a report from the American Heart Association,” Circulation, vol. 145, no. 8, pp. e153–e639, 2022.

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[3] D. Wurm, P. Ewert, P. Fierlinger, R. T. Wakai, V. Wallner, et al., “A small scale optically pumped fetal magnetocardiography system,” Journal of Clinical Medicine, vol. 12, no. 10, p. 3380, 2023.

[4] J. F. Strasburger, “Fetal magnetocardiography: Using quantum technologies to define fetal rhythm, conduction, and repolarization prior to birth,” American Heart Journal Plus: Cardiology Research and Practice, vol. 59, p. 100593, 2025.

Title	Portable Ultra-Low Field NMR Analysis System Based on MEMS Optically Pumped Magnetometer
Authors	Lun Zou[a], Ruyang Guo[a] , Yanjie Zhang[a], Yao Chen[a*] [a] School of Instrument Science and Technology, Xi′an Jiaotong University, Xi′an, 710049, China *yaochen@xjtu.edu.cn
Abstract	Optically pumped magnetometer (OPM)-based ultra-low-field nuclear magnetic resonance (ULF-NMR) provides a portable, cryogen-free platform for biochemical analysis. Translating this technology to in-field applications, such as point-of-care (POC) diagnostics, necessitates extreme system miniaturization. Here, we present a dual-mode OPM-ULF-NMR spectrometer architecture that bridges fundamental physical exploration with chip-scale sensing. The hardware development employs a parallel strategy. To facilitate fundamental studies, a ^{4}He optical pumping module featuring high-efficiency metastable excitation circuitry was developed. Conversely, for portable and high-sensitivity detection, microelectromechanical systems (MEMS) technology was utilized to integrate an alkali-metal vapor cell, miniature shielding coils, and a non-magnetic heating module into an ultra-compact magnetometer probe (43 × 12 × 15 mm). A fully customized embedded system synergizes these modules, executing closed-loop temperature control, microtesla-level NMR pulse scheduling, and synchronized data acquisition to systematically suppress internal magnetic noise. Using [1-^{13}C]-D-glucose as a representative analytical model, the system is configured to capture field-independent scalar coupling (J-coupling) fingerprints in microtesla environments. Initial engineering validations confirm excellent magnetic field homogeneity and signal acquisition capabilities, laying the rigorous hardware and theoretical foundation for forthcoming high-precision concentration measurements. This engineering paradigm offers a scalable framework for the development of future multi-scenario NMR analytical terminals.

Title	Low-power consumption SERF OPM for MEG
Authors	Zehuan Zhao[1], Kaiyan He[2], Yuyao Cai[1], Rui Yang[1], Yingchun Zhao[1], Zeyu Jin[1], Jia-Hong Gao[1,2] [1] Peking University, Beijing, China [2]Changping Laboratory, Beijing, China

Miniaturized magnetometers based on spin exchange relaxation free (SERF) have great potential in medical detection field such as MEG. To achieve SERF regime, the spin-exchange rate of alkali metal atoms has to be much higher than the Larmor precession frequency. Therefore, for the magnetometers using rubidium as the sensing atom, the vapor cell needs to be heated above 140 °C to obtain the required atomic density. For the miniaturized magnetometers, vapor cell with high temperature is usually placed close to the housing, which raises the housing temperature far above human body and increases heating power. Such high temperature may cause potential burn problem during hours long detection. Meanwhile, the excessive heating power consumption also degrades the device integration performance in MEG. In this research, using vacuum thermal insulation and radiation reflection layer, magnetometer's housing temperature and heating power consumption are greatly reduced while maintaining its miniaturization. The experimental results show that the outer temperature is reduced from 56 ℃ to 30 ℃, the heating power consumption is decreased from 660 mW to 300 mW, while maintaining high sensitivity. The vapor cell and optical component are assembled in low-thermal-conductivity structure and packaged inside a miniaturized Dewar. The vacuum layer (lower than 10^{-2} Pa) and silver thermal radiation reflection layer in Dewar suppress heat transfer between vapor cell and external environment, which reduces the outer shell temperature and heating power consumption.

Title	Movement-Related Magnetic Interference in Simultaneous OPM-MEG and fNIRS Motor Recordings
Authors	Urban Marhl[1], Pichaya Tappayuthpijarn[2], Stanislaw Wojtkiewicz[3], Piotr Sawosz[3], Adam Liebert[3], Tilmann Sander[2], Vojko Jazbinšek[1] [1] Institute of Mathematics, Physics and Mechanics, Ljubljana, Slovenia [2] Physikalisch-Technische Bundesanstalt, Berlin, Germany [3] Nalecz Institute of Biocybernetics and Biomedical Engineering, Warsaw, Poland

Wearable optically pumped magnetometer based magnetoencephalography (OPM-MEG) enables the study of brain activity during a wide range of tasks without restricting the subject's head movement. However, movement of the sensors within the residual magnetic field gradients introduces magnetic interference in the recorded signals.

We recorded OPM-MEG and functional near-infrared spectroscopy (fNIRS) data during a hand motor task involving repetitive ball squeezing [1]. Analysis of the OPM-MEG data revealed strong low-frequency responses (<5 Hz) occurring during the time interval of motor execution. An additional environmental OPM sensor was mounted on a rigid extension attached to the participant’s head and showed similar signal patterns, indicating that the observed responses didn’t originate from neural activity. It turned out that it is connected with slight (barely visible) head movements from the task execution.

To mitigate this interference, we applied homogeneous field correction (HFC) with the harmonic expansion [2]. This reduced the movement-related artifacts while preserving task-related signals. We found that incorporating environmental reference sensors improves the performance of HFC-based denoising.

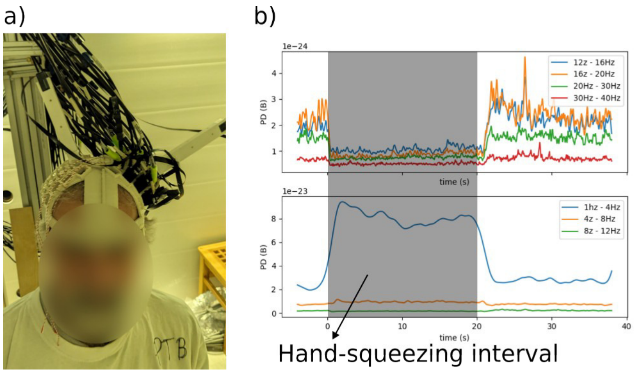

Figure 1: a) OPM-MEG and fNIRS measurement setup, with additional environmental sensors placed on the rods. b) Average MEG relative power for different frequency bands.

[1] P. Tappayuthpijarn, Neuroimage 325, 121644 (2026).
[2] T. M. Tierney, Neuroimage 258, 121644 (2022).

Title	All-optical measurement of the diffusion coefficient via vector light shift
Authors	Xingqing Jin[1], Wenlong Lyu[1], Yida Sha[1], Shuyuan Chen[1,2], Xiang Peng[1] [1] Peking University, Beijing, China [2] Helmholtz Institute, Mainz, Germany

The diffusion coefficient of alkali-metal atoms serves as an important parameter for characterizing motional averaging effects in anti-relaxation-coated vapor cells and determines the characteristic scale of magnetic-field-gradient-induced spin relaxation[1]. In this work, we propose an all-optical method for measuring the diffusion coefficient based on the light-shift effect. By exploiting the vector light shift and the spatial profile of a laser beam, an effective virtual magnetic field with a Gaussian distribution is generated inside the vapor cell[2], thereby modulating the atomic spin dynamics and relaxation process. Combined with free-induction-decay (FID) measurements, both the virtual magnetic field strength and the associated spin-relaxation information are characterized in situ. Experimental results show that the diffusion coefficient of the tetracontane-coated rubidium vapor cell is approximately 5.76 cm^2/s, which is in good agreement with the value of 6.17 cm^2/s independently obtained using the conventional magnetic-field-gradient method. The consistency between the two approaches verifies the validity of the proposed light-shift-based method for diffusion-coefficient measurements in coated vapor cells. This work offers a new route for investigating diffusion dynamics and spin relaxation in coated alkali vapor systems, with potential applications in atomic magnetometry, quantum sensing, and spatially resolved spin manipulation.

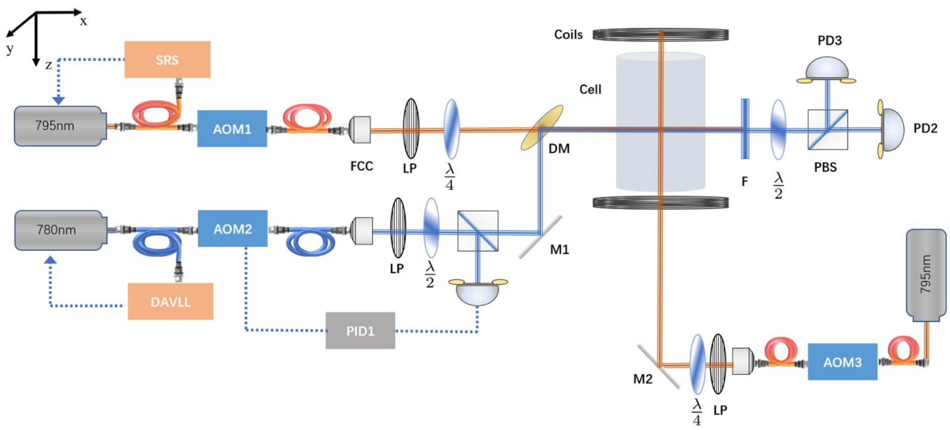

Figure 1: Schematic of the light-shift-based diffusion-coefficient measurement setup. FCC, fiber-coupled collimator; AOM, acousto-optic modulator; λ/2, half-wave plate; PBS, polarization beam splitter; λ/4, quarter-wave plate; PD, photodiode; LP, linear polarizer; DM, dichroic mirror; F, optical filter; M, mirror; DAVLL, Dichroic Atomic Vapor Laser Lock; SAS, Saturated Absorption Spectroscopy; PID, proportional-integral-derivative controller.

References

[1] J. Zheng et al., Phys. Rev. A 109, 022803 (2024).

[2] A. Berrebi et al., Phys. Rev. L. 135, 023201 (2025).

Title	Long-term Stable 3-Axis Vector Atomic Magnetometer Using a Commercial Rubidium Ampoule and Direct Absorption Frequency Lock
Authors	Yanfei Leng, Minaru Kawamura Okayama University of Science, Okayama, Japan

We present the development and field validation of a nanotesla-precision 3-axis vector optically pumped magnetometer (OPM) utilizing a commercial rubidium ampoule and a vertical-cavity surface-emitting laser (VCSEL). While OPMs achieve ultra-high sensitivity, maintaining long-term stability in unshielded, dynamic geomagnetic environments remains a significant challenge [1]. To address this, our system employs a robust single-beam architecture with orthogonal magnetic field modulation [2]. Furthermore, to effectively suppress the long-term thermal drift of the VCSEL, we implemented an active frequency stabilization mechanism based on a direct absorption curve (Fig. 1a). This direct absorption spectroscopy lock provides excellent wavelength stability without the optical complexity associated with saturated absorption setups. The long-term stability and practical viability of the sensor were validated through continuous geomagnetic field observations. Operating in an unshielded laboratory environment, our system successfully tracked dynamic geomagnetic phenomena over a multi-day period in July 2026. Specifically, the continuous vector measurement of the 3-axis geomagnetic field components showed excellent agreement with provisional reference data from the Kakioka Magnetic Observatory (Fig. 1b). This successful tracking of natural geomagnetic variations demonstrates the robust suppression of slow drift components in our compact, cost-effective OPM platform.

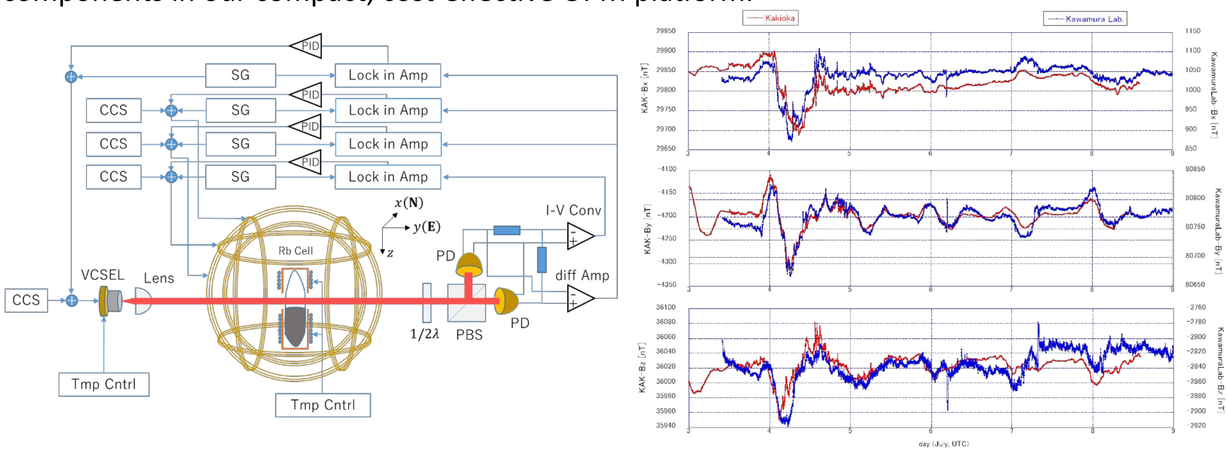

Figure 1 (a) (b)

Figure 1: (a) Block diagram of the magnetometer setup featuring a direct absorption frequency lock loop. The system operates in a closed-loop regime where 3-axis Helmholtz coils apply feedback currents to maintain a zero-magnetic-field condition at the rubidium vapor cell, effectively functioning as an active magnetic shield. (b) Continuous observation of the relative changes in the 3-axis geomagnetic field components in our unshielded laboratory. The variations, measured as feedback currents, are compared with provisional reference data from the Kakioka Magnetic Observatory in July 2026.

References: [1] M. Rosner, et al., Appl. Phys. Lett. 120, 161102 (2022). [2] Q. Guo, et al., Appl. Phys. Express 14, 066002 (2021).

Title	Millisecond-scale 3D OPM tracking for optically-blind droplet flows
Authors	Xinxin He[1], Haifeng Dong[2], Chenlu Xu[2], Jun Tang[1], Zongmin Ma[1], Jun Liu[1] [1] North University of China, Taiyuan, Shanxi, China [2] Beihang University, Beijing, China

Abstract: Quantitative 3D magnetic mapping of droplet streams is crucial for high-throughput biosensing and stimuli-responsive drug delivery. This work demonstrates an experimental free-induction-decay configuration for in-situ 3D field mapping and tracking of droplet flow within a hollow Rb-Cs vapor cell, leveraging of the RF pulse protocol and spin polarization transfer. A line laser sequentially and indirectly polarizes the consecutive layers of Cs atoms in the hybrid vapor featuring symmetric laser heating. After the pumping phase, a transverse π/2 RF pulse is immediately applied to rotate the spin orientation by 90◦. Then a broad probe laser will be undergoing Faraday-rotation during orthogonal transmission through the freely-precessing Cs atomic layer, and then projected onto a 2×8-channel differential photodetector array, thus allowing for the magnetism extraction from each voxel where the probe beam intersects an atomic layer. Finally, the frame rates of 6~24 fps were used to map the dynamic field distribution of suspension droplets, carrying several #2507 duplex stainless steel spheres, traversing the cell orifice, achieving a magnetic spatial resolution of 500 × 857 × 1000 μm^3, an accuracy of 1.27 nT@6fps under the 120-s duration, and a median sensitivity of 18.31 pT/√Hz@1~200Hz&21fps. It is highly suitable for velocimetry of multiple micrometer-scale tracers in flight, satellite droplet formation visualization, as well as for mapping the transverse relaxation time and diffusion coefficient of alkali atoms within the vapor cell.

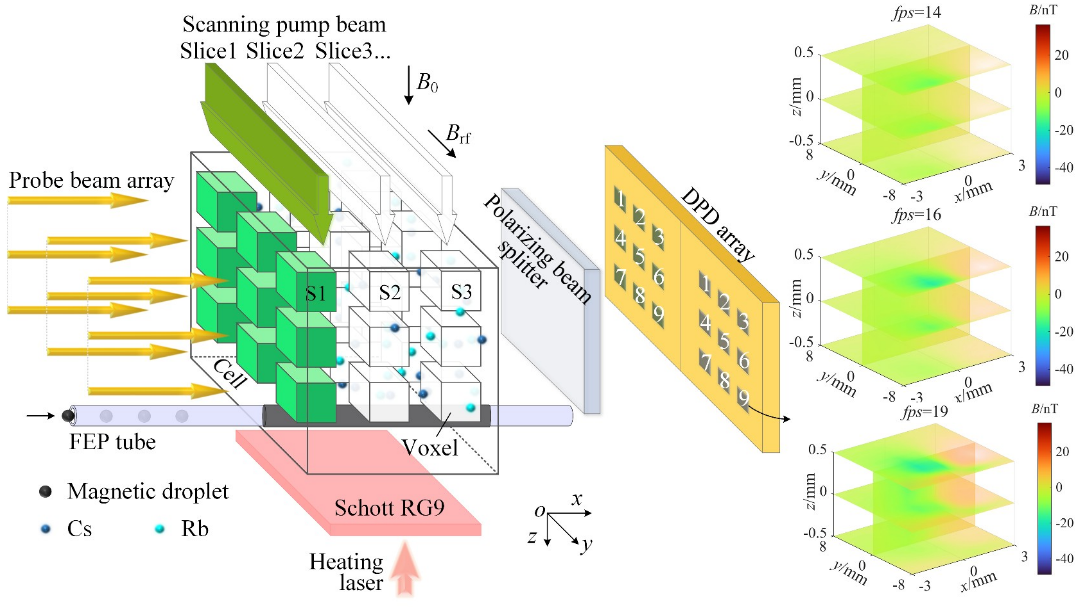

Figure 1. Principle of 3D OPM tracking method and partial keyframe results.

Title	Dual-Axis Decoupling Method for OPM Based on Longitudinal Modulation
Authors	Wen Luo[1], Ziqi Yuan[2], Shudong Lin[1], Yujian Ma[1], Guangshu Yu[1], Junjian Tang[1] , Yueyang Zhai[1] [1] Beihang University, Beijing, China [2] Hangzhou Institute of Extremely-Weak Magnetic Field Major National Science and Technology Infrastructure, Hangzhou, China

The development of high-sensitivity multi-axis vector atomic magnetometers has become a focal point in quantum sensing. However, the presence of cross-axis coupling in multi-axis vector measurements significantly degrades the measurement accuracy. To address this issue, we propose a dual-axis decoupling method for optically pumped atomic magnetometers based on longitudinal magnetic field modulation. Our study reveals that the longitudinal bias field exerts a significant influence on the dual-axis coupling degree. When the Larmor frequency induced by the longitudinal magnetic field matches the modulation frequency, the phases of the dual-axis responses under first-order demodulation tend to be orthogonal. By further optimizing the modulation amplitude, we achieve the complete separation of the dual-axis responses, thereby enabling full decoupling of the system.

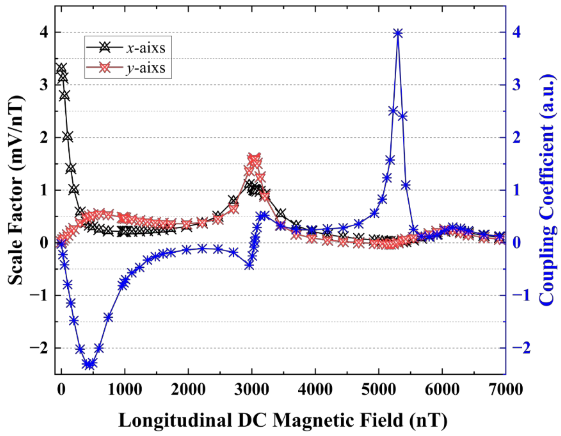

Figure 1. The influence of longitudinal DC magnetic field on dual-axis response.

Title	Multi-Channel SERF Atomic Magnetometer Array Based on Optical Diffractive Devices
Authors	Chenghui Zheng, Kun Yang, Chuangzhen Guo, Yafen Cai and Xiangyan K ong Ningbo University, Ningbo, Chin

Multi-channel spin-exchange relaxation-free (SERF) atomic magnetometers are crucial for high-spatial-resolution biomagnetic imaging, such as magnetoencephalography (MEG) and magnetocardiography (MCG) [1, 2, 3]. However, the development of high-density arrays remains inconsistencies across channels arising from non-uniform optical and magnetic field configurations. In this work, we present a multi-channel spin exchanged relaxation free atomic magnetometer array based on a diffractive optical element (DOE). Toavoid crosstalk, we quantified the dependence of atomic diffusion distanceon cell configuration and spin relaxation rate, thereby determining the tolerable channel spacing under optimal magnetometer conditions. To resolve the critical issue of array inconsistency, the DOE was utilized to guarantee uniform multi-beam splitting. Further, an in-situ compensation method for environmental magnetic fields and magnetic field gradients was proposed, further improving the consistency of the sensors' magnetic field responses. Experimental results demonstrated that the full width at half maximum (FWHM) of the zero-field magneticresonance line is 26±1.5 nT, and the magnetometer sensitivity reaches 20±5 fT/Hz1/2@10Hz with a bandwidth of 136±5Hz. The deviation in magnetic field responseacrossthe magnetometer array is less than 1%. This work provides an importantfoundation for high fidelity, rapid magnetic imaging of small organs, including fetaland small animal hearts

[1] Kominis I K, Kornack T W, Allred J C, et al. A subfetotesla multi channel atomic magnetometer. Nature, 2003, 422(6932): 596-599.
[2] Boto E, Holmes N, Leggett J, et al. Moving magnetoencephalography towards real-world applications with a wearable system. Nature, 2018, 555(7698): 657-661.
[3] Wyllie R, Kauer M, Smetana G S, et al. Magnetocardiography with a modularspin-exchange relaxation-free atomic magnetometer array. Physics in medicine and biology, 2012, 57(9): 2619-2632

Title	Towards actively shielded MEG using zero-field optically pumped magnetometers
Authors	Eemeli Luostarinen[1] and Joonas Iivanainen[1] [1] Aalto University, Espoo, Finland

Magnetoencephalography (MEG) typically requires heavy and expensive magnetic shielding. We aim to develop a portable actively shielded MEG system with zero-field optically pumped magnetometers (OPMs).

We have built a tabletop prototype system with two nested three-axis Helmholtz coil sets and two fluxgate magnetometers. One fluxgate inside the coils provides negative feedback for the coils and a second external fluxgate drives feedforward compensation. The compensation algorithms are implemented on a microcontroller. The system combines DC compensation, lock-in type feedforward compensation for mains noise, and a PI controller for low-frequency interference.

Without compensation, the peak-to-peak (ptp) values inside the coils were 27–85 nT and the DC field magnitude was approximately 50 uT. With compensation, this was reduced below 18 nT on all axes (0–150 Hz). These preliminary results indicate that we should be able to run a commercial OPM with a dynamic range of tens of nT inside the system. Next we will operate an OPM inside the system, implement more complex compensation algorithms and build a system that can house a whole-head OPM array.

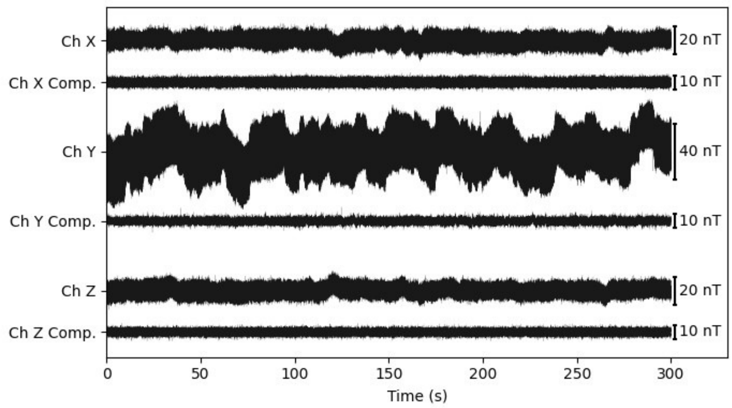

Fig. 1 Time series for compensated and uncompensated fluxgate axes.

Title	High-sensitivity Operation of Unshielded Radio-frequency Atomic Magnetometers
Authors	Han Yao[1], Longjie Zhao[2], Ferruccio Renzoni[2] [1]School of Physics, Nanjing University of Science and Technology, Nanjing, China [2]Department of Physics & Astronomy, University College London, London, UK

Atomic magnetometers (AMs) have been attracting growing interest due to their extreme sensitivity, low cost, and potential for miniaturization. A wealth of scenarios where AMs may play a pivotal role have been explored: from magnetocardiography and magnetoencephalography to magnetic nanoparticles detection, and electromagnetic induction imaging.
The proofs of concept of the extreme sensitivity of AMs are typically performed in magnetically controlled environment, with mu-metal enclosures used to shield against detrimental ambient noise. This allows one to explore the fundamental sensitivity limits. However, real-world applications often require the operations of AMs in unshielded environment. This has stimulated the exploration of strategies to be able to retain high sensitivity in the presence of magnetic noise. Here we review our work to achieve high-sensitivity operation of radio frequency AMs. We will show that the suppression of low-frequency magnetic noise allows for high-sensitivity operation in the RF range, and discuss several strategies and operational modes demonstrated to this purpose.
[1] H. Yao, B. Maddox, and F. Renzoni, High-sensitivity operation of an unshielded single cell radio-frequency atomic magnetometer, Opt. Express 30, 42015 (2022).
[2.] H. Yao and F. Renzoni, High-sensitivity operation of unshielded radio-frequency atomic magnetometers using phase-lock techniques, IEEE Trans. Instrum. Meas. 74, 9535009 (2025).
[3.] H. Yao, L. Zhao, T. Ma, and F. Renzoni, Fast electromagnetic induction imaging with unshielded radio-frequency atomic magnetometers in phase-lock mode, IEEE Trans. Instrum. Meas. 74, 8007907 (2025).

Title	OPM–MEG for pediatric speech processing: Voice-evoked responses in children and adults and comparison with SQUID–MEG
Authors	Yuko Yoshimura[1,2,3,] Takashi Ikeda[2,3], Eiichi Okumura[2,3], Chiaki Hasegawac,[4], Mitsuru Kikuchi[2,3,5] 1.Faculty of Education, Institute of Human and Social Sciences, Kanazawa University, Kanazawa, Japan;2.Research Center for Child Mental Development, Kanazawa University, Kanazawa, Japan; 3.United Graduate School of Child Development, The University of Osaka, Kanazawa University, Hamamatsu University School of Medicine, Chiba University and University of Fukui, Suita, Japan ; 4.Institute for Promotion of Diversity and Inclusion, Kanazawa University, Kanazawa, Japan; 5.Department of Psychiatry and Behavioral Science, Graduate School of Medical Science, Kanazawa University, Kanazawa, Japan

Abstract starts here and only one page is allowed.

Magnetoencephalography (MEG) is a potential tool for investigating the neural dynamics underlying auditory and language development in children. However, conventional superconducting quantum interference device (SQUID)-based MEG systems have limitations in pediatric recordings because of their fixed sensor geometry and the requirement for cryogenic cooling. Optically pumped magnetometer MEG (OPM–MEG) provides a wearable alternative that enables sensors to be placed closer to the scalp; however, empirical evidence regarding its feasibility in children remains limited. In this study, we recorded OPM–MEG responses to the Japanese syllable /ne/ in children and adults. We further compared the pediatric OPM–MEG data with data obtained from a separate group of children using a conventional SQUID–MEG system. Early auditory-evoked responses consistent with the P1m component were observed in both adults and children, with spatially organized magnetic field distributions over the left temporal sensors [1]. The longer latency observed in children was consistent with established developmental trajectories that reflect cortical maturation. A comparison with SQUID–MEG revealed similar P1m latencies in the pediatric groups. Signal-to-noise ratio analyses further indicated that, although the baseline noise was higher in OPM–MEG recordings, higher signal amplitudes were observed during the active response window, resulting in broadly comparable response detectability between the two systems. These findings provide foundational evidence that OPM–MEG can reliably capture voice-evoked P1m responses in children and support its potential application in developmental and clinical speech neuroscience.

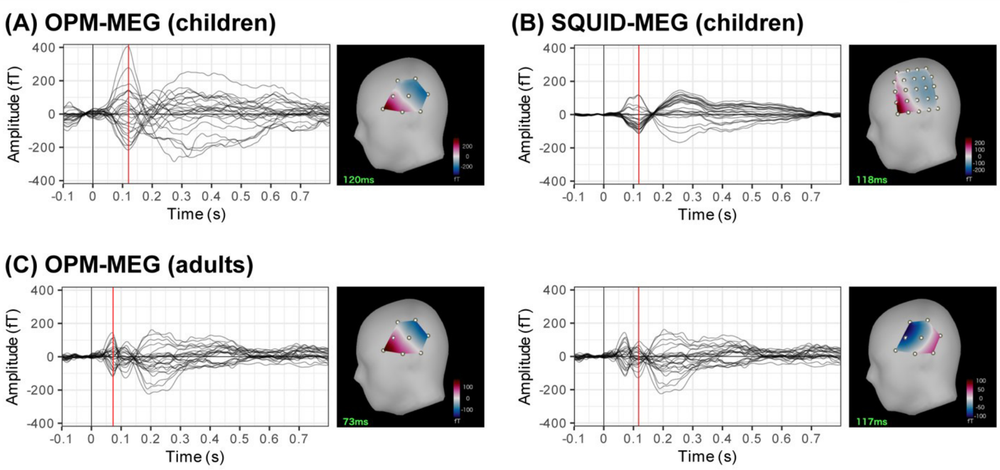

Figure 1: Grand-averaged OPM–MEG waveforms evoked by the speech sound /ne/ in children and adults.

[1] J.E. Oram Cardy, NeuroReport, 15(12), 1867–1870. (2004).

Title	Demagnetization procedure for a person-sized magnetic shield
Authors	Olli Pikkarainen[1], Paavo Hietala[1], Markus Henttonen[1], Joonas Iivanainen[1] and Lauri Parkkonen[1]. [1]Aalto University, Department of Neuroscience and Biomedical Engineering, Espoo, Finland

Magnetoencephalography (MEG) measurements are conventionally performed in a large magnetically shielded room (MSR). The emergence of optically pumped magnetometers (OPMs) has enabled the use of more compact magnetic shields. However, OPMs require a near-zero ambient field to operate, which can be achieved through passive and active magnetic shielding. To this end, we are developing an OPM-MEG system that employs a person-sized shield (PSS).

Ferromagnetic shielding materials consist of microscopic domains whose magnetic moments align when exposed to external magnetic fields, leading to residual magnetization even after at aligning field is removed. To minimize this residual field, the performance of passive shielding is enhanced through demagnetization. The process uses a decaying alternating current waveform that initially drives the material into magnetic saturation. As the alternating magnetic field gradually decreases, the magnetic domains become randomly oriented, thereby reducing the remanent field inside the PSS.

Here, we present a complete demagnetization system for the PSS. We have optimized the demagnetization waveform and sequence, developed hardware for coil control, and created custom software for intuitive operation. We evaluated the performance of the demagnetization using OPMs. The demagnetization procedure consistently reduced the residual magnetic field within the shield's target volume from approximately 20 nT to 5 nT following purposeful magnetization, enabling high-resolution OPM-MEG measurements.

Title	Cerebellar tactile expectations measured using OPM-MEG
Authors	Laura Bock Paulsen[1], Lau Møller Andersen[1,2] [1] Department of Linguistics, Cognitive Science and Semiotics, Aarhus University, Denmark [2] Department of Clinical Medicine, Center of Functionally Integrative Neuroscience, Aarhus University, Denmark

Although the cerebellum is often overlooked in MEG research, recent simulation and empirical studies have demonstrated the feasibility of cerebellar recordings. However, whole-head OPM-MEG has not been applied to study the cerebellum yet.

We recorded whole-head OPM-MEG data from 31 healthy participants performing two tactile discrimination tasks with electrical stimulation of the index and middle fingers, designed to investigate cerebellar contributions to spatiotemporal tactile expectations during perceptual decision-making.

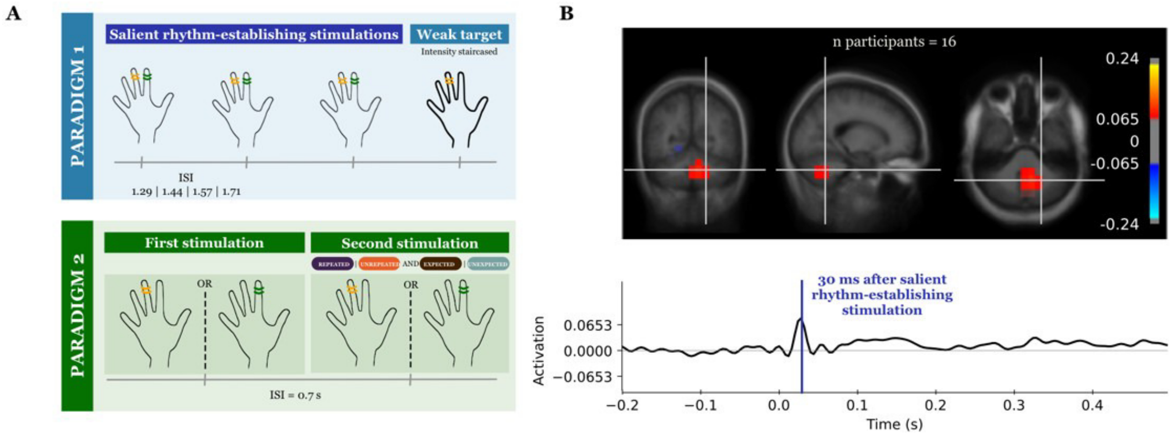

Figure 1: A) Tactile discrimination paradigms designed to investigate cerebellar contributions to spatiotemporal tactile expectations. B) Preliminary source reconstruction of evoked responses to simultaneous electrical stimulation of the index and middle fingers using an LCMV beamformer.

Preliminary analyses show clear somatosensory-evoked activity in source space and support the feasibility of investigating cerebellar activity with OPM-MEG.

Title	Research on atomic magnetometers based on vortex beam
Authors	Guoan Cai, Chenyao Zhan, Zhaoying Wang

We conducted in-depth research on atomic magnetometer schemes based on scalar and vector vortex beams. We first proposed a spin-exchange-relaxation-free (SERF) atomic magnetometer scheme based on weak measurement principle and enhanced by structured light. By introducing a scalar Bessel Gaussian vortex beam (BG) carrying orbital angular momentum (OAM) into the magneto-optical rotation (MOR) detection process, we have improved magnetic field sensitivity by utilizing enhanced spin orbit interactions and weak value amplification effects.

Radially polarized light has a spatially axisymmetric polarization structure. We studied the synergistic relationship between the spatial intensity distribution of radially polarized light and the direction of the magnetic field based on the polarized thermal atom ensemble. This is intuitively presented in the polarization selective absorption effect of thermal atoms, allowing the vector information of the magnetic field to be embedded into the geometric characteristics of the transmitted light field intensity distribution. Based on this, we use a dual beam scheme of the radially polarized light detection and the linearly polarized light pumping, combined with the absorption ratio and projection coefficient of the transmission intensity pattern, to infer the three-dimensional direction of the magnetic field. Furthermore, we propose an optical design scheme for an atomic vector magnetic field sensor based on a single radially polarized light. This scheme uses relevant detection methods to analyze the orientation angle of the transmitted light spot and combines it with the light intensity absorption ratio to detect the three-dimensional directional distribution of the vector magnetic field.

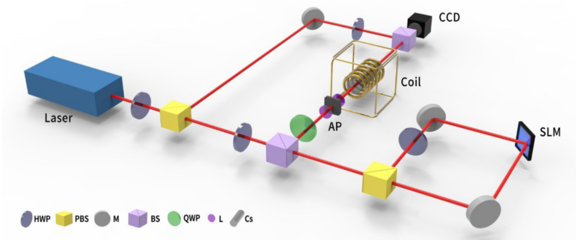

Figure 1. Schematic diagram of experimental setup. HWP: half-wave plate; QWP: quarter-wave plate; M: mirror; L: lens; PBS: polarization beam splitter; BS: beam splitter; SLM: spatial light modulator; CCD: charge coupled device; AP: 4F aperture system; Coil: magnetic field coil; Cs: cell.

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