Contents

Program

CT: Contributed Talk, IS: Invited Speaker
All times are Central European Summer Time (CEST)

Monday, 4th October

	Applications of OPMs		
9:30–9:40	Welcome to WOPM 2021!		
9:40–10:20	IS	**Georg Bison** Paul Scherrer Institute, Switzerland	Atomic magnetometry in precision experiments for the nEDM collaboration
10:20–10:40	CT	**Emmanuel Klinger** Johannes Gutenberg-Universität Mainz, Germany	Magnetometry with amplified spontaneous emission from sodium vapors
10:40–11:00	CT	**Hector Masia-Roig** Helmholtz Institute Mainz, Germany	Search for Axion domain walls using the Global Network of Optical Magnetometers for Exotic physics (GNOME)
11:00–11:30	Coffee break		
11:30–11:50	CT	**Jiong Huang** Beihang University, China	Highly sensitive atomic comagnetometer for rotation rate measurement with a low-pressure K-Rb-^{21}Ne vapor cell
11:50–12:10	CT	**Patrick Bevington** National Physical Laboratory, UK	Radio-frequency atomic magnetometer for defect detection and object surveillance
12:10–12:30	CT	**Rudy Romain** CEA-Leti, France	A metastable helium-4 OPM for medical imaging
12:30–12:50	CT	**Charikleia Troullinou** ICFO, Spain	Squeezed-light enhancement of sensitivity and signal bandwidth in an optically-pumped magnetometer

	Medical applications		
15:00–15:40	IS	**Igor Savukov** Los Alamos National Laboratory, USA	Multi-channel radio-frequency optically pumped magnetometers and their applications in MRI
15:40–16:00	CT	**Kyung-min An** Kanazawa University, Japan	Auditory-evoked fields and auditory steady-state responses measured by optically pumped magnetometers
16:00-16:20	CT	**Stefan Hartwig** PTB Berlin, Germany	Magnetomyography with Optically Pumped Magnetometers
16:20–16:40	Coffee break		
16:40–17:00	CT	**Matthew Brookes** University of Nottingham, UK	Triaxial OPMs: Next generation of wearable MEG?
17:00–17:20	CT	**James Lubell** Aarhus University, Denmark	Contactless measurement of retinal activity using optically pumped magnetometers
17:20–17:40	CT	**Justus Marquetand** University of Tübingen, Germany	Possibilities in clinical neurophysiology
17:40–18:00	Poster flash session		
18:00	Virtual poster session		

Tuesday, 5th October

	New measurement schemes		
9:30–10:10	IS	**Chris Perrella** University of Adelaide, Australia	High-bandwidth optical magnetometry via phase retrieval
10:10–10:30	CT	**Dominic Hunter** University of Strathclyde, UK	An accurate magnetometer based on Ramsey-style interrogation
10:30–10:50	CT	**Tianhao Liu** Helmholtz-Institut Mainz, Germany	A hybrid pumping spin-exchange-relaxation-free (SERF) atomic gyroscope using parametric modulation
10:50–11:20	Coffee break		
11:20–11:40	CT	**Qianqian Yu** University of Science and Technology of China, China	Bell-Bloom magnetometer driven by pump beams off-resonant with the atomic transitions
11:40–12:00	CT	**Philipp Treutlein** University of Basel, Switzerland	Towards optical quantum control of nuclear spins in a Helium-3 gas
12:00–12:20	CT	**Weijia Zhang** Beihang University, China	Optical rotation detecting for atomic spin precession based on Mach-Zehnder interference
12:20–12:40	Poster flash session		
12:40–15:00	Virtual poster session		

	Emerging techniques		
15:00–15:40	IS	**Morgan Mitchell** ICFO, Spain	Optically-pumped magnetometry and comagnetometry with Bose-Einstein condensates
15:40–16:00	CT	**John Bainbridge** Sandia National Laboratories, USA	An actively controlled dual species Rb atomic magnetometer for low frequency communication
16:00-16:20	CT	**Anton Vershovskii** Ioffe Institute, Russia	Single-beam all-optical nonzero-field sensor for MEG
16:20-16:40	CT	**Amir Borna** Sandia National Laboratories, USA	Cross-Axis Projection Error in Optically Pumped Magnetometers and its Implication on Magnetoencephalography Systems
16:40–17:00	Coffee break		
17:00–17:20	CT	**Molly Rea** University of Nottingham, UK	Towards open scanning environments for wearable MEG
17:20–17:40	CT	**Joonas Iivanainen** Sandia National Laboratories, USA	A pulsed vector optically pumped magnetometer operating in the SERF regime
17:40–18:00	CT	**Stuart Ingleby** University of Strathclyde, UK	Feedback and bandwidth in self-oscillating and radio-frequency OPMs
18:00–18:10	Concluding remarks		

Virtual Poster Sessions

Monday, 4th October

Applications of OPMs - Link 1	
Denis Brazhnikov	High-Quality Level-Crossing Resonances in a Cesium Vapor Cell for Applications in Atomic Magnetometry
Thomas Coussens	Modular optically-pumped magnetometer system
Edward Irwin	Single Beam Caesium SERF Magnetometry for MEG
Aaron Jaufenthaler	Towards unshielded magnetorelaxometry imaging of magnetic nanoparticles using pulsed OPM
Ross Johnston	An RF magnetometer for low-field NMR measurements
Reinis Lazda	Nanotesla sensitivity, compact NV center based vector magnetometer
Eric Miller	Laser-based comagnetometry for neutron electric dipole moment experiments at TRIUMF
Marcin Mrozowski	Ultra-low noise, scalable, bi-polar current source, for use as a coil driver in optically pumped magnetometers
Mikhail Padniuk	Transient exotic spin coupling search with noble-gas alkali-metal co-magnetometers
Piotr Put	Spin-gravity coupling limits based on ultra-low-field NMR comagnetometers

New Measurement Schemes - Link 2	
Rachel Dawson	Machine Learning for Multi-Parameter Optimisation for a Zero-Field Optically Pumped Magnetometer
Tino Fremberg	Towards detection of individual magnetotactic bacteria using optically pumped magnetometers
Peter James Hobson	An active–passive magnetically-shielded test-bed for optically pumped magnetometers
Niall Holmes	Naturalistic hyperscanning with wearable magnetoencephalography and matrix coil magnetic field control
Chris Kiehl	An Accurate Rabi Vector Magnetometer Implemented with Hot Alkali Vapor
Gwenael Le Gal	^{4}He zero-field vector optically pumped magnetometer operated in the Earth magnetic field
Volkmar Schultze	Optically pumped magnetometer with omnidirectional magnetic field sensitivity
Yuliya Javier Velarde	Towards a Mobile, and Magnetically Quiet Optically Pumped Magnetometer
Jim Webb	High-speed microcircuit and synthetic biosignal widefield imaging using nitrogen vacancies in diamond

Tuesday, 5th October

Medical Applications - Link 1	
Yulia Bezsudnova	Optimization of the MEG-OPM sensor for environmental conditions
Philip Broser	Optically pumped magnetometers reveal fasciculations non-invasively
Sarang Dalal	Preliminary evidence of fetal magnetoencephalography with optically pumped magnetometers
Isabel Gale	Detection of fetal biomagnetic signals using optically pumped magnetometers
Lauren Gascoyne	Muscle OPM signal modulates with force output
Aikaterini Gialopsou	Spatio-temporal measurements of visually-evoked fields using optically-pumped magnetometers
Ryan Hill	Beta-band dynamics during motor learning
Victor Lebedev	Low stand off optical magnetometer for biomedicine
Urban Marhl	Noise impact on different OPM-MEG measuring components
Natalie Rhodes	The frequency response of an OPM: A steady-state visual evoked response MEG study
Lukas Rier	Motor task fingerprinting using OPM-MEG

Emerging Techniques - Link 2	
Andris Berzins	Compact device for applying magnetic field designed for NV based magnetic field microscopy
Guzhi Bao	Design of coaxial coils using hybrid machine learning
Riccardo Cipolletti	Prediction of NMR Gyroscope Performance using Numerical Modelling
Terry Dyer	MEMS Cs vapour cell with 10mm optical path length
Lucy Edwards	Towards active magnetic field cancellation on a moving array of OPMs
Vincent Jonany	High-Density OPM-Array Simulations for Clinical Brain-Computer Interfaces (BCI)
Allan McWilliam	Free-induction-decay magnetometry using a dual-laser configuration
Haoying Pang	Performance of Integrated ferrite shield in a K-Rb-21Ne co-magnetometer
Florian Wittkaemper	Functionalization of micro-fabricated alkali vapor cell arrays
Shuhe Wu	Entanglement-Assisted Magnetic Gradiometer under Ambient Conditions
Peiyu Yang	Coherence protection of electron spin in Earth-field range by all-optical dynamic decoupling

List of Abstracts – Talks

Atomic magnetometry in precision experiments for the nEDM collaboration

G. Bison[1]

[1]Paul Scherrer Institute, Villigen, Switzerland

Many precision experiments use precessing spins as sensitive probes to various aspects of nature. Typically, those experiments observe the precession frequency of electronic or nuclear spin systems and search for weak correlations of those frequencies with the physical effect under investigation. This principle will be illustrated using the example of the neutron EDM experiment at PSI. Because of the strong coupling of the precession frequency to the magnetic field, it is of critical importance to isolate such experiments from magnetic field disturbances. At PSI we will use a combination of active and passive magnetic shielding as well as more than 100 auxiliary magnetometers to control and monitor the magnetic field in the experiment. The performance of this system will be reviewed and potential applications of similar systems for magnetometer tests and bio-magnetometry will be discussed.

Magnetometry with amplified spontaneous emission from sodium vapors

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The measurement of Earth magnetic field is an extremely important topic in geophysical research; measurements in the range 10-300 km can only be acheived with stand-off magnetometry. Current techniques, based on resonant scattering from atoms or molecules, are often limited by low collection efficiency [1]. In the mean time, the generation of a directional laser-like emission, amplified spontaneous emission (ASE), from a sodium vapor cell was recently reported [2].

Here we demonstrate, on a table-top experiment, the detection of the sodium ground-state free-precession under the influence of an external magnetic field by recording the intensity of the backward-directed ASE, see Fig. 1. This method enables scalar magnetometry in the Earth field range without the need of calibration which is extremely suitable for remote sensing using the sodium layer in the mesosphere.

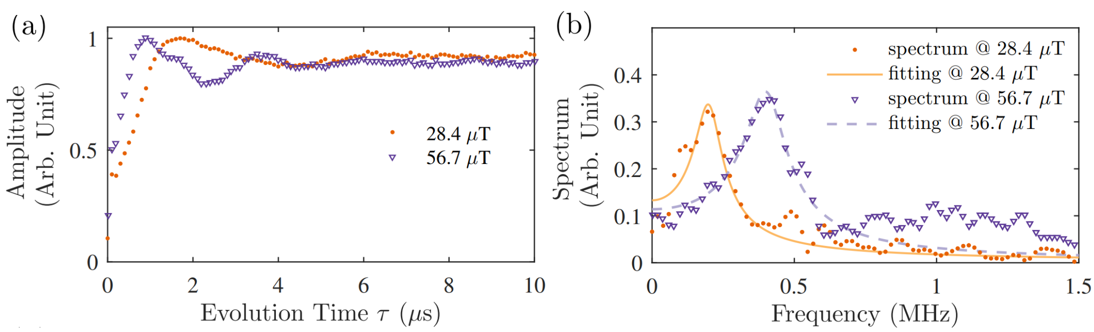

Figure 1: Sodium ground-state free-precession detected with ASE. (a) ASE intensity as a function of the evolution time. (b) Fourier transform of the ground-state free-precession.

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Search for Axion domain walls using the Global Network of Optical Magnetometers for Exotic physics (GNOME)

Hector Masia-Roig[1,2], and Joseph A. Smiga[1,2] on behalf of the GNOME collaboration

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The Global Network of Optical Magnetometers for Exotic physics (GNOME) is a network of geographically separated, time-synchronized atomic magnetometers and comagnetometers in magnetically shielded environments [1]. This configuration allows monitoring the Zeeman levels' energy splitting of an atomic ensemble continuously and simultaneously at different places around the globe.

Axion-like particles (ALP) could form topological defects in the form of domain walls. The transit of a domain wall through Earth may alter the levels energy splitting in atoms which can be measured with atomic magnetometers. A time-domain analysis method was applied to the data gathered by GNOME in order to identify possible domain-wall events [2]. We concluded that no significant signals are present in the GNOME science run performed between the 29th of November and the 22nd of December 2017. The sensitivity of the GNOME to domain walls during this science run was evaluated and the parameter space of the ALP which form domain walls was constrained [3].

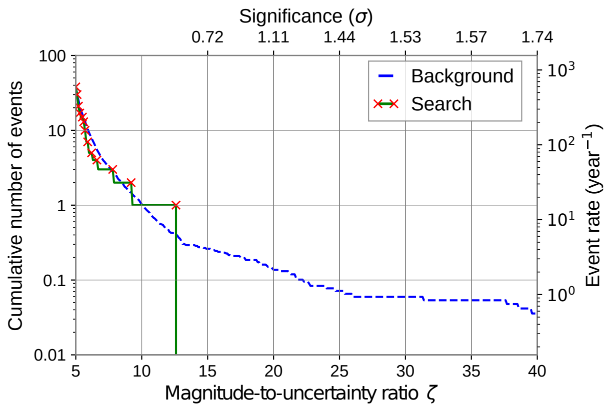

Figure 1: Significance of the events found in the search data with respect to the background.

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[2] H.Masia-Roig, J. A. Smiga et al., Physics of the Dark Universe, **28**, 100494 (2020).
[3] S. Afach, Ben C. Buchler et al., arXiv:2102.13379v2.

High sensitive atomic co-magnetometer for rotation rate measurement with a low-pressure K-Rb-^{21}Ne vapor cell

Jiong. Huang[1], Wenfeng Fan[1], Kai Zhang[1], Linlin Yuan[1], Hongyu Pei[1], and Wei Quan [2]

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The atomic co-magnetometer (ACM) has been widely used in fundamental physics research such as tests of Lorentz and CPT violation, searches for anomalous spin forces, and electric dipole moments. Besides, it also has the potential to be a miniaturized gyroscope for inertial navigation due to its ultra-high sensitivity to the rotation rate[1]. However, various disturbances degrade the performance of the ACM in the practical environment. A typical disturbance is the low-frequency magnetic field noise. Although this noise can be suppressed by the self-compensation mechanism of the hybrid atomic spin ensembles, the suppression effect is limited and highly susceptible to system parameters[2]. We report Here the self-compensation characteristics of the hybrid atomic spin ensembles in the ACM with a low-pressure K-Rb-^{21}Ne vapor cell (less than 1 atm). The experimental results show that the hybrid atomic spin ensembles in the low-pressure environment have a stronger ability to suppress low-frequency magnetic field noise than those in the high-pressure environment. The rotation rate measurement sensitivity and the long-term performance of the ACM can be improved by approximately 1.7 times and 1.5 times respectively under the optimized conditions. The influence of the vapor cell temperature on the self-compensation capability of the hybrid atomic spin ensembles is also studied.

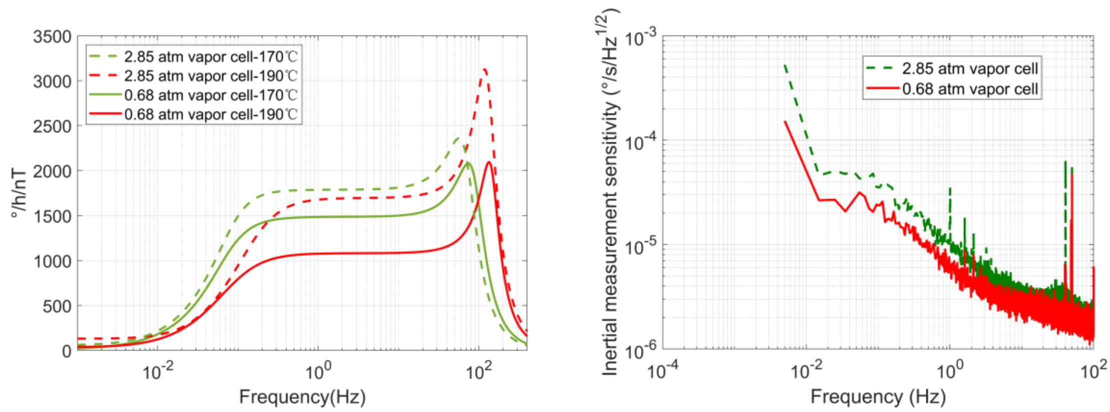

Figure 1: Amplitude-frequency response (Left) under the transverse magnetic field excitation and inertial measurement sensitivity (Right) of the ACM with different pressure vapor cells.

References

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Radio-frequency atomic magnetometer for defect detection and object surveillance

P. Bevington[1] and W.Chalupczak[1]

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Instruments based on radio-frequency inductive technologies (Magnetic Induction Tomography) create an exciting alternative to standard defect detection and object surveillance methods, e.g. ultrasound, infra-red or visible imaging. The rf atomic magnetometer brings superior sensitivity to inductive measurements, in addition to a range of functionalities; the ability for vectorial rf field measurement, a high bandwidth when operated in the self-oscillating (spin maser) mode, and tunability over a wide frequency range without compromising performance.

The inductive response of an object to an oscillating magnetic field reveals information about its electrical conductivity and magnetic permeability. We demonstrate that it is possible to determine the object’s composition by measuring the angular, frequency, and spatial dependence of the inductive response. Identification is performed by referencing the object's response to that from materials with mutually exclusive properties such as copper (high electric conductivity, negligible magnetic permeability) and ferrite (opposite). This technique uses the difference in object response generated by eddy currents and magnetisation. Possible applications of the technique in security screening devices are discussed.

Additionally, we will explore the benefits of combining properties of the atomic magnetometer (e.g. the presence of an insensitive axis with the ability of vector field measurement and the symmetry of the primary radio-frequency field) to enhance this inductive imaging technique in both the free running (external drive for the radio-frequency field) and in the spin maser mode.

(a) (b)

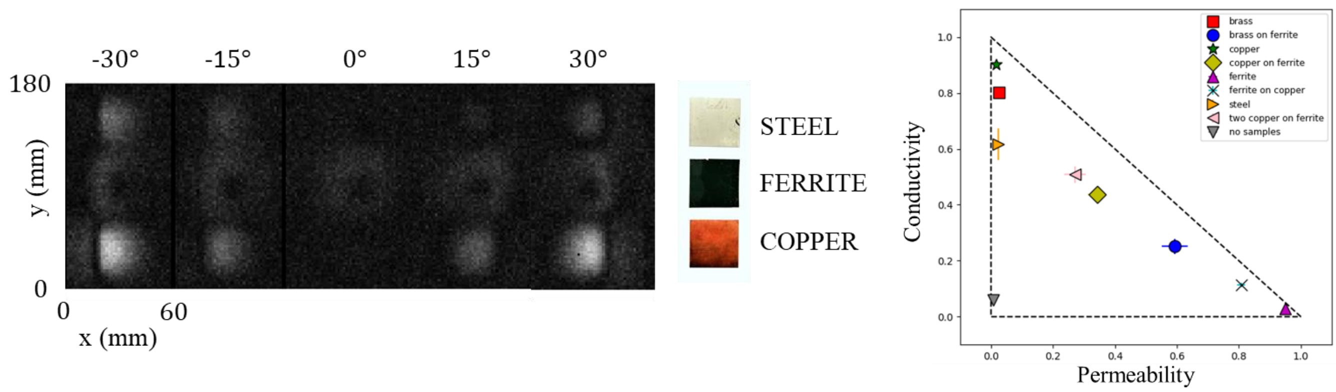

Figure 1: (a) Images of three different material types recorded via Magnetic Induction Tomography indicating a different angular response. (b) Determination of material type by analysing angular scans using machine learning techniques.

A metastable helium-4 OPM for medical imaging

R. Romain[2], S. Mitryukovskiy[1], W. Fourcault[1], V. Josselin[1], M. Le Prado[1,2], E. Labyt[1,2] and A. Palacios-Laloy[1,2]

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Our team works on OPM based on a gas of helium-4 atoms excited to their F=1 metastable state, which can be significantly populated by using a low-intensity rf discharge of only a few mW. This species has been used in scalar OPMs for Space exploration, notably the one of the Swarm missions that was commissioned by ESA to our team [1].

Since helium is a gas at room temperature no heating of the sensitive element is needed. This allows operating the magnetometers at any temperature, and notably in direct contact with patient skin or scalp without any thermal discomfort.

A full rework of our helium-4 OPM has allowed us to obtain sensors with more compact footprints than previously. In contrast with other OPM metastable helium-4 atoms being a spin-one species, we can optically pump atoms with linearly polarized light, yielding atomic alignment [2]. This configuration allows measuring the component of the field radial to the head using light that propagates radially, which allows closer packing and a simpler optical setup.

Thanks to numerous improvements, the intrinsic noise of the sensor has been reduced to less than 50 $fT/Hz^{1/2}$, in the close vicinity of the photon noise of the probe laser. Closed-loop operation where the local magnetic field is continuously canceled thanks to 3-axis compensation coils, allows a virtually unlimited dynamic range. Our sensors currently have a 2-kHz bandwidth, a dynamic range of >300nT [3].

We have currently set up an array of 5 magnetometers working in closed-loop with automatic correction of the cross-talks between the sensors. This array of sensors is being tested in three medical trials for different neurology and cardiology applications.

References

[1] I. Fratter et al., Acta Astronautica **121**, 76 (2016).
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[3] W. Fourcault et al., Opt. Express **29**, 14467 (2021).

Squeezed-light enhancement of sensitivity and signal bandwidth in an optically-pumped magnetometer

Charikleia Troullinou[1], Ricardo Jiménez-Martínez[1,2] , Jia Kong[1,3], Vito-Giovanni Lucivero[1] and Morgan W. Mitchell[1,4]

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Optical and atomic quantum noise in magnetometry can be reduced by optical squeezing and spin squeezing, respectively. Here we study how squeezed light probing affects the sensitivity spectrum of a high-density quantum noise limited OPM with 300 fT/$\sqrt{\text{Hz}}$ sensitivity. Using off-resonant polarization squeezed light generated in a subthreshold optical parametric oscillator [1] we probe a polarized ensemble of ~10^{13} atoms/cm^3 and increase the signal to noise ratio. [2] In contrast to previous squeezed-light enhanced magnetometers [3], [4], [5], the atomic Bell Bloom excitation along with the dispersive readout of this setup enable independent optimization of the spin preparation and probing while supporting continuous QND measurements. At the same time, it allows clear theoretical understanding of the different quantum noise contributions. The use of squeezed probe light is shown (both experimentally and theoretically) to improve the high-frequency sensitivity as well as the signal bandwidth of the OPM while also evading back action noise.

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[3] Wolfgramm et al, Phys. Rev. Lett. **105**, 053601, (2010)
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Multi-channel radio-frequency optically pumped magnetometers and their applications in MRI

Igor Savukov [1] **and Young Jin Kim** [1]

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Radio-frequency optically pumped magnetometers (RF OPMs) can operate in a broad frequency range from kHz to MHz with a bias field tuning. Their sub-fT sensitivity is promising for many applications, including magnetic resonance imaging (MRI). At Los Alamos, we have designed a multi-channel RF OPM with the goal of applications in multi-channel parallel MRI at ultra-low field (Fig.1).

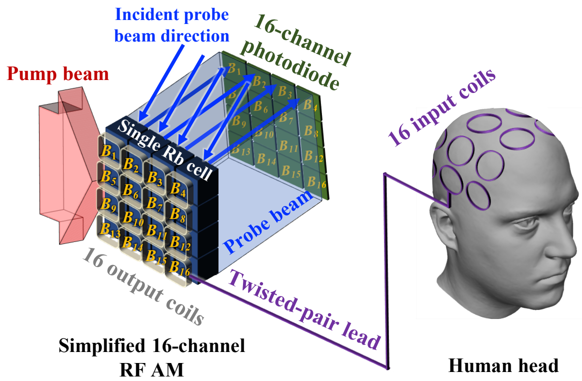

Figure 1: Illustration of the multi-channel OPM parallel ULF MRI device.

A long-standing problem in MRI applications is that an OPM would lose its sensitivity in the presence of the MRI fields and gradients. A simple solution, compatible with anatomical imaging, is to use a flux transformer (FT) that carries out only the RF component of MRI signals into the OPM. In a multi-channel FT-OPM system, it is important to sufficiently reduce crosstalk between FTs. According to our analysis, an array of partially overlapping pick-up coils in a non-resonance operation can minimize the mutual flux between the FTs. In contrast, an array of pick-up coils would require a resonant operation to reach fT sensitivity without OPMs, which would make the FT decoupling a very challenging technical problem. We performed theoretical simulations [1] to address the FT decoupling question and estimated the sensitivity of the multi-channel FT-OPM system. In this talk, we will report our progress on the multi-channel MRI and related questions, such as design of low-noise 100 aT RF shield [2] from which MRI and other high-sensitivity OPM applications will greatly benefit. This work is supported by LANL LDRD program, grant # 20200393ER.

References

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Auditory-evoked Fields and Auditory Steady-state Responses measured by Optically Pumped Magnetometers

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Magnetoencephalography (MEG) is a functional neuroimaging technique, which non-invasively detects the brain magnetic fields generated by neurons. The auditory steady-state responses (ASSR) at 40 Hz have shown the altered gamma band activities in patients with schizophrenia, bipolar, and autism spectrum disorders [1,2]. Recently, small-sized optically pumped magnetometers (OPMs) have been developed and commercialized. OPMs do not require cryogenic cooling and can be placed within millimeters from the scalp. Here, we arranged 6 OPM sensors on the temporal area to detect the auditory-related brain responses in a two-layered magnetic shielded room. We presented the auditory stimuli of 1-kHz pure tone with 200-ms duration and found the M50 and M100 components of the auditory-evoked fields. We delivered the periodic stimuli with a 40-Hz repetition rate and we observed clear ASSR at 40 Hz. Our results indicate the feasibility of using OPM sensors to detect ASSR at 40 Hz for future clinical study.

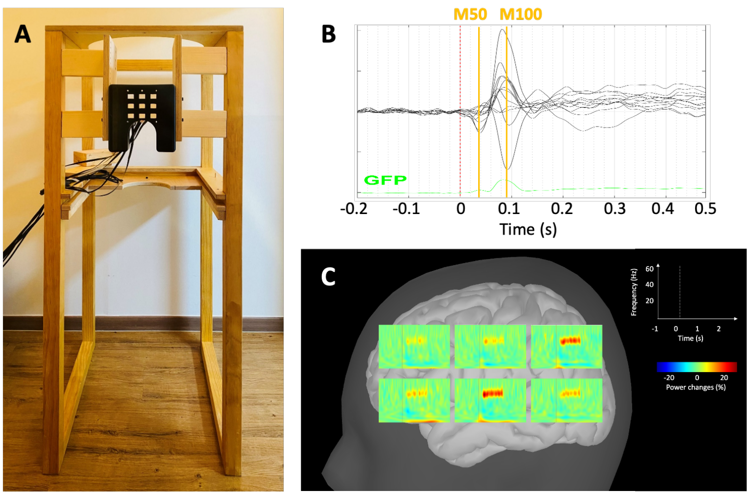

Figure 1: OPM sensor array and the auditory brain responses. A) OPM array to detect brain activities from the temporal area. B) The grand-averaged auditory-evoked fields across 22 participants show obvious M50 and M100 components. C) The grand-averaged time-frequency representations show the ASSR at 40 Hz.

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Magnetomyography with Optically Pumped Magnetometers

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Magnetomyography (MMG) is a promising method in neurophysiology, as it may possibly be able to replace the invasive and painful needle-electromyography (needle-EMG). The latter, being the daily applied gold standard in neurophysiology to diagnose the functional operation of skeletal muscles. In contrast to MMG performed with superconducting quantum interference device (SQUID)-systems, sets of OPMs may not have a fixed spatial arrangement. Instead they can be flexibly put close to the muscle or directly fixed onto the skin. This flexibility together with the option to use small compact magnetic shields might be game-changing. We will present and compare MMG measurements of stimulated muscle responses performed with SQUIDs and OPMs in different modalities under the especially quiet magnetic field conditions as they are provided inside PTB's Berlin Magnetically Shielded Room (BMSR-2.1). While the 304 sensors in PTB's SQUID-system have fixed positions inside the cryogenic dewar, which comes along with an increased sensor-to-body distance, the 8 QuSpin QZFM-gen-2.0 OPMs were employed twofold. Once in a row above the body like the SQUID-system (lab-fix), and second directly placed onto the skin (body-fix) and thus with minimal possible sensor-to-body distance. We compare the measurements with respect to the achieved signal-to-noise ratio as well as the temporal structure of the signals and discuss benefits and limitations of current commercial OPMs in MMG, also in contrast to surface and needle-EMG.

Towards open scanning environments for wearable MEG

Molly Rea[1], Niall Holmes[1], Ryan M. Hill[1], Elena Boto[1], James Leggett[1], Lucy J. Edwards[1], Natalie Rhodes[1], Vishal Shah[2], James Osborne[2], David Woolger[3], Eliot Dawson[3], T. Mark Fromhold[1], Paul Glover[1], P. Read Montague[4], Richard Bowtell[1]and Matthew J. Brookes[1].

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As the building blocks of a MEG system, OPMs offer the potential for unrestricted participant movement. However, this potential can only be realised if background magnetic fields are well controlled.

Here we present a magnetic field mapping technique that uses a moving array of OPMs, worn in a rigid helmet, to determine the strength and spatial variation of the background field, which was described via a spherical harmonic model. An equal and opposing magnetic field was then applied via an array of bi-planar, electromagnetic coils [1]. The remnant magnetic field at the centre of the coils was reduced from 1.3 ± 0.3 nT to 0.27 ± 0.09 nT (Fig. 1A), giving a 5-fold reduction in 0—2 Hz interference.

A limitation of this approach was that magnetic field nulling could only be achieved over a fixed volume at the centre of the coil planes due to the coil design, thus restricting scanning to within that central volume. To overcome this, we developed an adaptable, 'matrix coil' active magnetic shielding system [2]. The matrix coil is formed from a series of 48 square unit coils that can cancel the remnant magnetic field at any location within the region bounded by the coil units, since the currents applied to the individual coils can be reconfigured. Initial demonstrations of this matrix coil system enabled mapping of sensorimotor cortex activity in two interacting participants, who were scanned simultaneously whilst playing a 'bat and ball' game (Fig. 1B).

While the matrix coil system affords flexibility in the location of one or more nulled regions, our magnetic field modelling and control technique provides an ultra-low field environment for OPM-MEG studies. Future work will aim to combine these approaches to generate a reconfigurable nulled region with ultra-low remnant magnetic field.

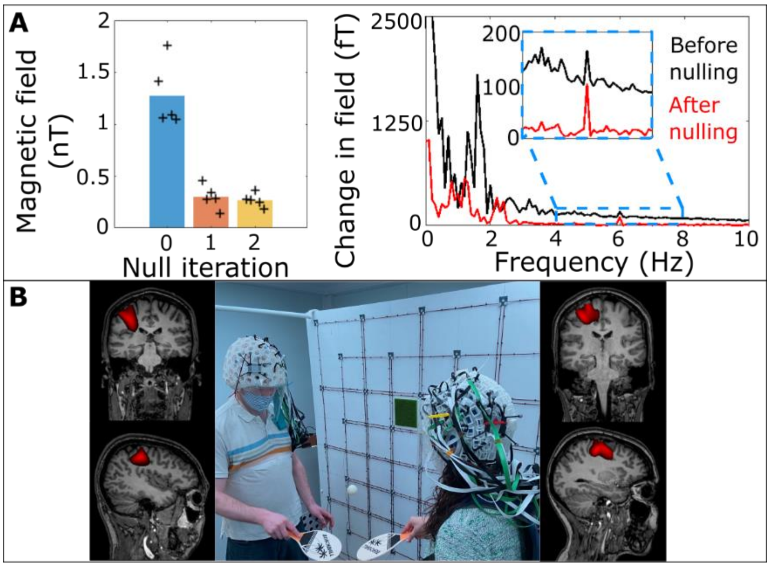

Figure 1: A) *Left:* The norm of the remnant magnetic field is given by the bar chart – before nulling is shown in blue, after one null in orange and after two nulls in yellow. The mean value over 5 repeats is given by the bars, the data by the crosses (+). *Right:* FFT of data from a single sensor during a visual steady-state evoked response experiment with 6 Hz stimulation. SNR of 6 Hz peak is increased while low-frequency artefact was decreased by nulling (red). B) The matrix coil system enables two participants to be scanned while playing a ball game. Images show activity in the left motor regions of both participants.

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Contactless measurement of retinal activity using optically pumped magnetometers

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Because OPM sensors can be placed more flexibly and can measure neuronal structures other than neocortex, we used OPM sensors to measure human retinal activity following flash stimulation. Comparison of the magnetoretinographic (MRG) activity to a simultaneously recorded electroretinogram showed the familiar flash-evoked potentials (a-wave and b-wave) and shared a highly significant amount of information with the electroretinogram recording. Full details of this study are available as a pre-print [1]. Current work focuses on whether high frequency retinal activity (100-150 Hz) can also be measured using OPMs.

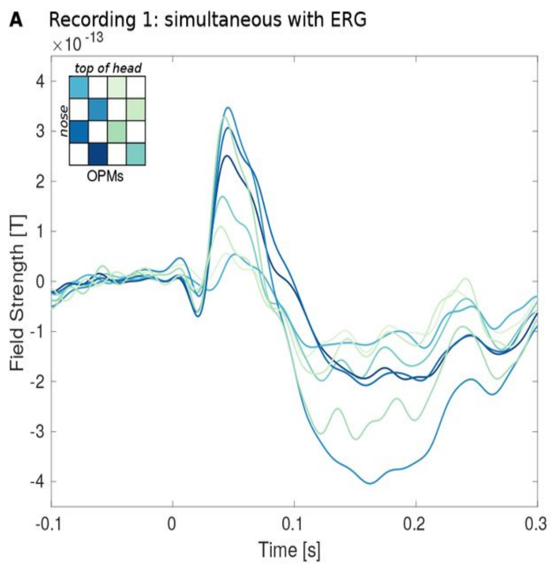

Figure 1: OPM recording of retinal activity in response to light flashes. Traces show activity measured by OPM sensors, averaged across participants during a simultaneous ERG recording of the contralateral eye.

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Possibilities in clinical neurophysiology

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It is an open quest to evaluate performance and potential benefits of optically pumped magnetometer (OPM) in clinical neurophysiology.
This contribution discusses the performance, pitfalls, as well as the possibilities and limitations of OPM through multiple proof-of-principle experiments involving the measurement of various evoked potentials. In particular, we demonstrate that OPM are partially capable to measure evoked potentials of the retina (magnetoretinography, MRG), visual cortex (visual evoked potentials, VEP), somatosensory pathways (somatosensory evoked potential, SEP, see Figure 1), and muscle intrinsic reflexes - and furthermore - to gain new insights: For example, based on the vectorial analysis of the magnetic flux signal of peripheral nerves, brain or muscles, new perspectives in the investigations of neurophysiology are possible since the spatial information of e.g. propagating action potentials can be measured.
This contribution provides insights on the possibilities of OPM as well as its potential in neurophysiology.

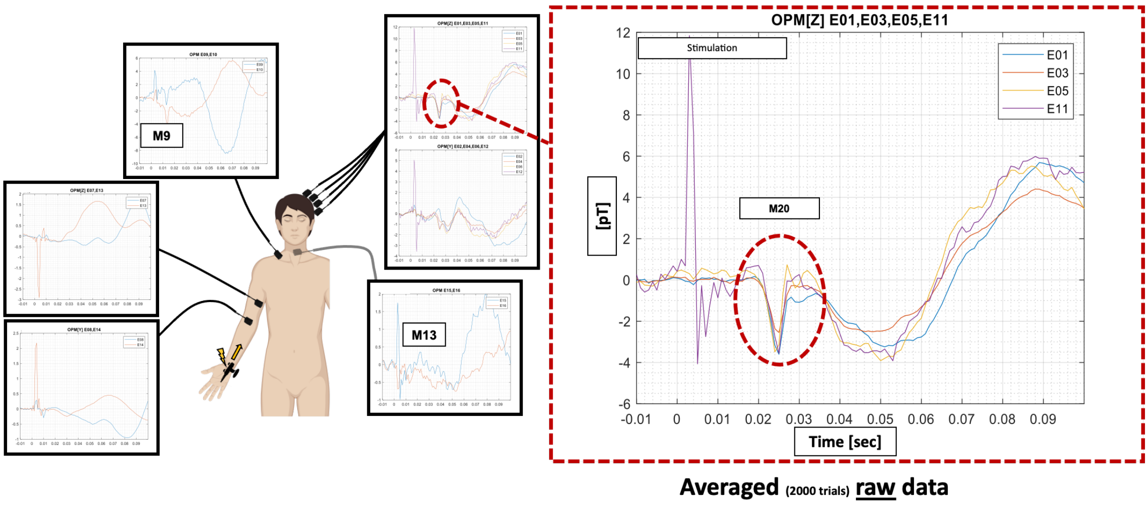

Figure 1: Illustration of the electrically evoked sensory responses with M9 located over Erb's point, M13 of the spinal cord, and M20 in the parietal lobe area.

High-bandwidth optical magnetometry via phase retrieval

Chris Perrella[1], **Kyle Netz**[1], **Rujie Li**[1], **Andre Luiten**[1]

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We demonstrate broadband, high-bandwidth magnetic field measurements from DC to above 1MHz with a magnetometer based on nonlinear magneto-optical rotation (NMOR). This is achieved through measurement of the instantaneous phase evolution of the optical polarisation rotation in the temporal domain. We theoretically show that this instantaneous phase evolution can be extracted directly from polarimeter measurements through balancing the absorption and polarisation rotation of the probe light. Under these conditions, the two outputs of the polarimeter are phase shifted by 90° allowing the instantaneous phase to be calculated. We combine the instantaneous phase measurements [1] with phase sensitive detection and active feedback techniques [2] to track magnetic field fluctuations over long timescales resulting in broadband, high-bandwidth magnetic field measurements from DC to above 1MHz, nearly 4-orders of magnitude larger than the passive bandwidth. This technique achieved a sensitivity of 200fT/$\sqrt{\mathrm{Hz}}$ around 8Hz and 1nT/$\sqrt{\mathrm{Hz}}$ at 100kHz, for a bias field of 50μT [2]. We present bandwidth and signal-to-noise ratio (SNR) measurements, Figure 1, and demonstrate that NMOR magnetometers are able to offer high-bandwidth and broadband field measurements for oscillating fields from DC to above 1MHz. Practical and physical limitations to the technique will be discussed.

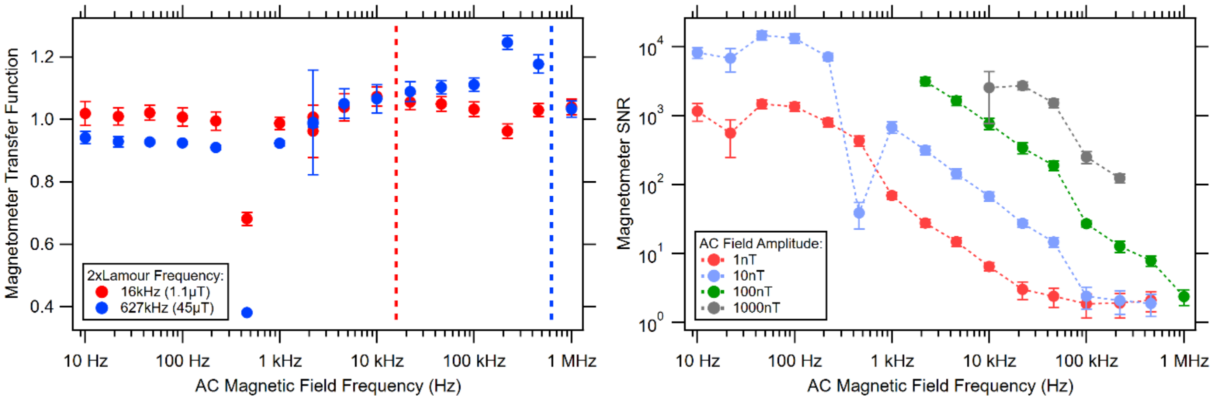

Figure 1: Left - Transfer function of the instantaneous phase retrieval technique. Vertical dashed lines represent twice the Lamour frequency, the polarization rotation modulated frequency. Right – SNR measurements for a range of magnetic field strengths.

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An accurate magnetometer based on Ramsey-style interrogation

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We implement an interrogation mode analogous to Ramsey spectroscopy [1], enabling observation of spin dynamics unperturbed by optical fields. Similar readout methods have been employed previously to measure ground state coherences [2]. The basic principle involves optically pumping an atomic ensemble into a well-defined quantum state that subsequently evolves during a dark period. This is succeeded by a time-delayed probe pulse that measures the spin phase at the instant readout began. The intrinsic spin dynamics can then be reconstructed by superimposing the signals observed at various delay times, manifesting as precession and partial relaxation experienced during the dark interval.

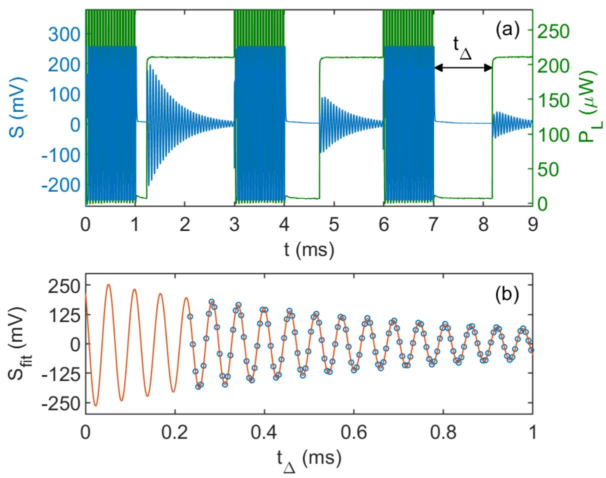

Figure 1: (a) FID signal train subsection, and corresponding laser power prior to illuminating the vapor cell which is set close to zero for a time, t_Δ, after optical pumping. (b) Reconstructed precession signal exhibiting spin dynamics unperturbed by the $210\,\mu\mathrm{W}$ readout field.

This phase-sensitive measurement enables accurate magnetic field tracking as AC Stark shifts are effectively suppressed. Additionally, reduction in power broadening introduced by residual optical pumping provides a platform for assessing the intrinsic relaxation properties of the vapor cell. This method is highly favourable compared to previously adopted techniques that extrapolate to zero-light power [3], as elevated laser intensities can be used to significantly improve SNR.

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A hybrid pumping spin-exchange-relaxation-free (SERF) atomic gyroscope using parametric modulation

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For next generation inertial navigation systems of vehicles, atomic spin gyroscopes are promising rotation sensors due to their high sensitivity and relatively compact active volume. The group of Michael Romalis first demonstrated in 2005 a spin-exchange-relaxation-free (SERF) atomic gyroscope that relys on polarised alkali-metal vapor and nobel gases co-located in a glass cell [1]. The realised sensitivity of 5.0×10^{-7} rad/s/$\sqrt{\text{Hz}}$ is already comparable with devices in the < 50 cm scale.

We present a dual-axis SERF atomic gyroscope using hybrid pumping and parametric modulation. Hybrid pumping can essentially reduce the polarization gradient, and leads to a better sensitivity [2]. To circumvent low frequency drifts, we employ the parametric modulation technique which modulates the direction of the atomic spin polarisation by an oscillating magnetic field in conjunction with lock-in detection. Compared to the light modulation techniques, such as a Faraday modulator or a photoelastic modulator, parametric modulation reduces costs and benefits miniaturization [3].

We will describe the experimental setup and model the coupled spin system under parametrical modulation. Additionally, we compare the performance when the modulation field is added in different axes. At the end, we will present simulation results of single beam SERF gyroscopes and identify feasible conditions for realizing high sensitivity.

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Bell-Bloom magnetometer driven by pump beams off-resonant with the atomic transitions

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When the pump beam is modulated at frequencies close to the atomic Larmor frequency, a substantial atomic polarization can be built up even when the pump beam is orthogonal to the bias field, and this leads to the Bell-Bloom magnetometers. In this work, we present the results of the Bell-Bloom magnetometers when the pump beams are detuned from the atomic transitions, which has been largely neglected before. We study such effects in two different operation modes of the magnetometers. For the two-beam mode of the magnetometer, as shown in Fig. 1(a), we focused on the relation between the phase of the demodulated probe signal and the orientation of the bias field. Such a relation is strongly dependent on the pump beam detuning, and we can such an effect to improve the vector magnetometer sensitivity to the bias field orientation. For the single-beam mode of the magnetometer, as shown in Fig. 1(b), we studied the line shapes of the magnetometer response as a function of the modulation frequencies. Such a response is always symmetrical when the pump beam are resonant, however, it become asymmetrical when the pump beams are off-resonant from the atomic transitions, and non-orthogonal to the bias field. This effect is an important source of the heading error for the scalar magnetometers in the practical use, and we present an experimental solution to such a problem.

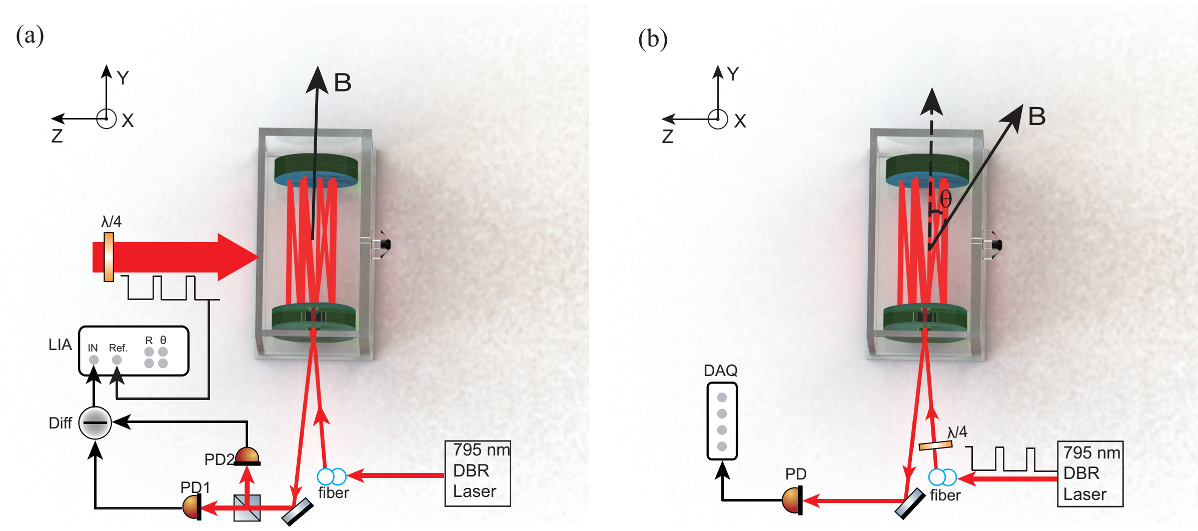

Figure 1. The two operation modes of the Bell-Bloom magnetometer.

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

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

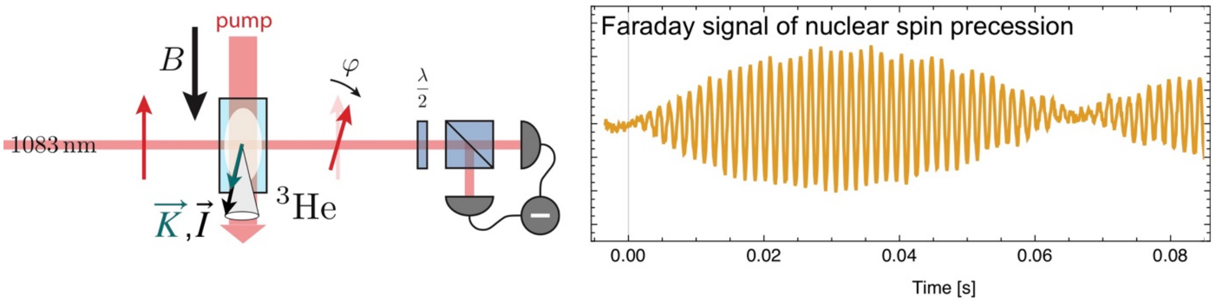

Figure 1: Optical Faraday measurement of Helium-3 nuclear spin Rabi oscillations.

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Optical rotation detecting for atomic spin precession based on Mach-Zehnder Interference

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In an atomic spin-exchange relaxation-free (SERF) inertial measurement system, the fluctuation of probe light power greatly limits the improvement of inertial measurement sensitivity. Different from the traditional polarization detection method which measures the change of probe light power to obtain the information of optical rotation induced by atomic spin polarization, a novel polarization detection method based on Mach-Zehnder interferometry technique is proposed and theoretically analyzed in this paper. In this method, an electro-optic phase modulated laser is used as the interferometric measurement source, and the atomic spin polarization is obtained by measuring the phase difference between the two arms of the interferometer. The output of the interferometry is independent of probe light power, which avoids systematic error caused by probe light power fluctuation. At the same time, high frequency electro-optic modulation is used in this method, and the low frequency noise, such as 1/f noise, can be effectively suppressed. The method proposed in this paper can improve the sensitivity and long term stability of the atomic spin inertial measurement system.

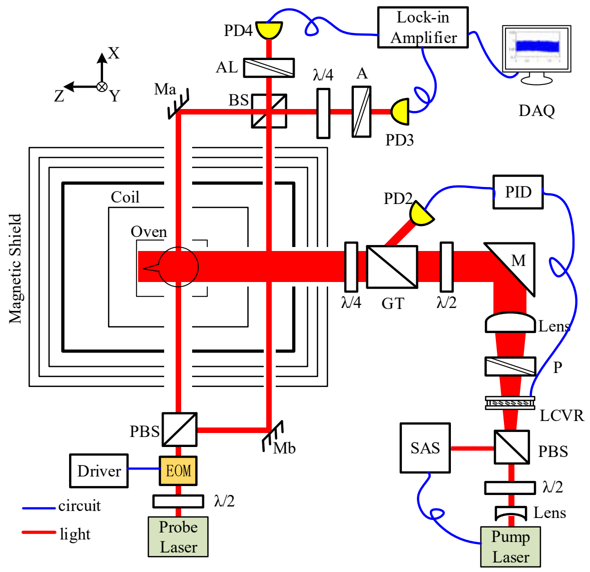

Figure 1: Schematic of experimental setup. EOM: electro-optic phase modulator, PBS: polarizing beam splitter, BS: beam splitter, M: mirror, A: nalyzer, PD: photodiode, DAQ: data acquisition system. LCVR: liquid crystal phase retarder, GT: Glen Taylor prism. P: polarizer, λ/2: half wave plate λ/4: quarter-wave plate SAS: Saturation absorption module

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Optically-pumped magnetometry and comagnetometry with Bose-Einstein condensates

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Spin coherence is central to the performance of atomic sensors. In vapor-phase OPMs [1], and in solid-state spin-based sensors such as NV diamond [2], two-body interactions, e.g. collisions and dipole-dipole coupling, make the spin relaxation rate scale as the spin number density. This, along with spin projection noise, create a quantum limit for E_R, the energy resolution per unit bandwidth [3], a figure of merit for time- and space-resolved magnetometry. In contrast, a Bose-Einstein condensate (BEC) can have fully-coherent two-body interactions [4], and thus no limit on E_R. Recently, BEC sensors are starting to be used for imaging of magnetic structures in condensed matter systems [5,6], making plausible the idea that BEC sensors could have real applications. In this talk I will describe our own studies on optically-pumped magnetometers [7] and co-magnetometers [8] using Bose-condensed ^{87}Rb as an atomic medium. We break a long-standing record for E_R [7], and suggest a new application for these exotic sensors: the search for axion and axion-like dark matter [8].

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Single-Beam All-Optical Nonzero-Field Sensor for MEG

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We present a magnetometric sensor scheme, which uses a single laser for optical pumping, magnetic resonance (MR) excitation, and MR probing. MR is excited by the modulation of circularly polarized component of the beam, and detection is achieved in a quantum nondestructive manner by the linearly polarized component. This allows us to significantly simplify the Bell-Bloom scheme [1], while retaining its sensitivity [2].

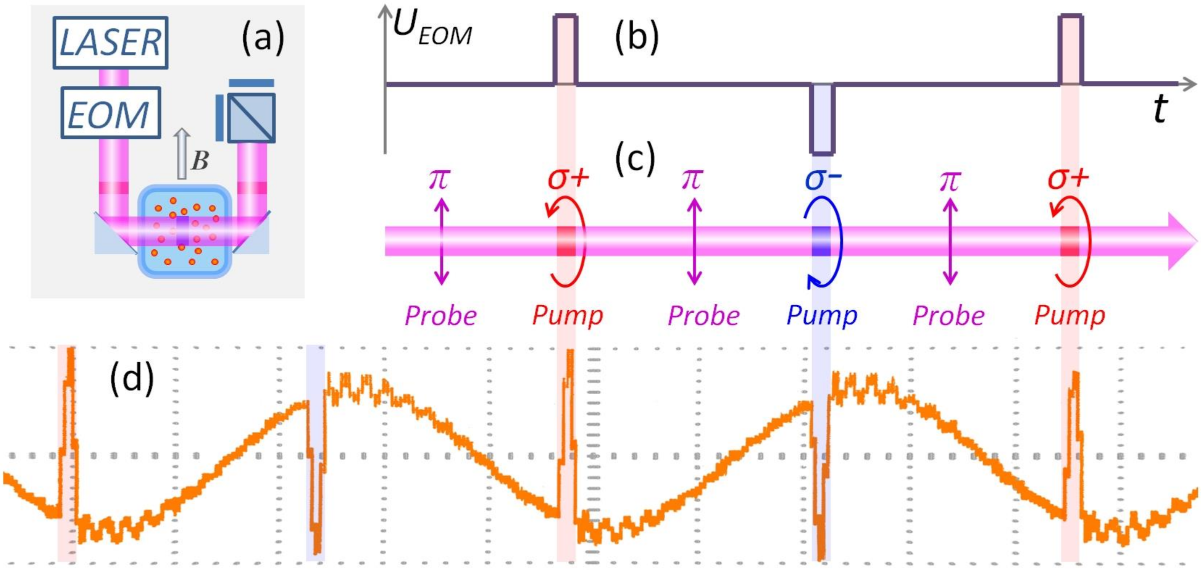

Figure 1: (a) Simplified setup diagram; (b) EOM control voltage; (c) one modulation period: $\sigma^{\pm}$ – circular polarizations, π – linear polarization; (d) Larmor precession signal.

A single beam is tuned to a frequency close to the F = I–½ ↔ F' = I±½ transitions of the $S_{1/2}$ state of an alkali metal (in our work, we use Cs); this beam depletes the F = I–½ level, and populates and strongly polarizes the F = I+½ level, forming the stretched state. Therefore the π-component of the beam, which we use for probe, mainly detects the MR at a level from which it is detuned by ~9 GHz. This provides the appropriate conditions for nondestructive quantum detection; thus, we achieve near-optimal conditions for both pumping and probing. Fig.1 shows a version that uses high duty cycle pulse pumping, which makes it possible to further reduce the MR width.

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An Actively Controlled Dual Species Rb Atomic Magnetometer for Low Frequency Communication.

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We present a radiofrequency (RF) atomic magnetometer based on natural abundance rubidium vapor for communications through lossy media. By utilizing both ^{85}Rb and ^{87}Rb, we build upon the variometer concept first presented by Alexandrov et al [1] and the atomic RF magnetometers first built at Princeton [2]. We have constructed a variometer using ^{87}Rb to obtain the full external field vector, which allows for active stabilization of the Larmor resonance of ^{85}Rb at the desired frequency via an FPGA-based feedback system. We have also designed a 3D-printed miniaturized housing for our physics package. Here we report on our progress toward a highly sensitive, fieldable magnetometer for low frequency communications in lossy media that can operate outside a magnetic shield.

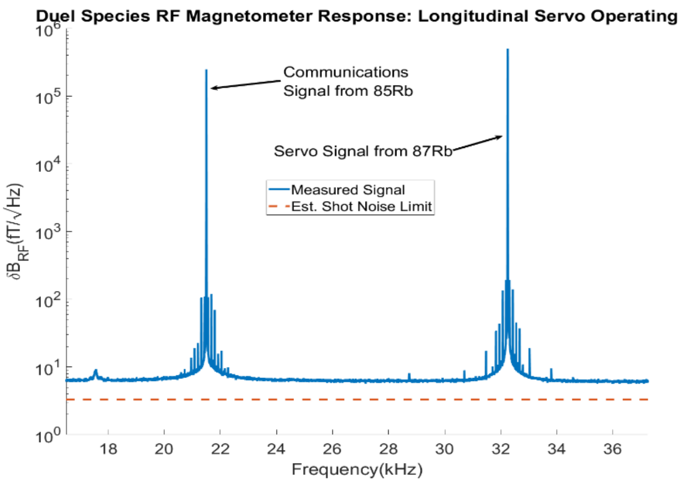

Figure 1: Preliminary data from the operation of our dual species magnetometer with longitudinal feedback engaged, demonstrating our ability to servo the magnetic field using ^{87}Rb whilst simultaneously detecting a communications signal from ^{85}Rb with good noise performance.

Funding Statement

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

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Cross-Axis Projection Error in Optically Pumped Magnetometers and its Implication on Magnetoencephalography Systems

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Abstract

The sensitivity of optically pumped magnetometers (OPMs) can be greatly enhanced by operating it in a spin-exchange-relaxation-free (SERF) regime, where the alkali atoms' spin exchange rate is much faster than Larmor precession frequency. SERF regime accommodates a wide range of remnant static magnetic field. In the presented work, through simulation and experiment, we demonstrate that multi-axis magnetic signals in the presence of small remnant static magnetic fields, not violating the SERF criteria, can introduce significant error terms in OPM's output signal. For this deterministic noise, we have dubbed the term cross-axis projection error. Furthermore, we have analyzed the detrimental impact of the OPM's cross-axis projection error on the localization capability of OPM-based magnetoencephalography systems (OPM-MEG).

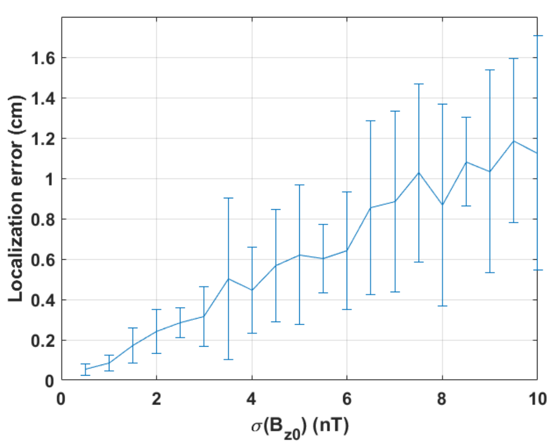

Fig. 1: The mean and standard deviation (bars) for source localization error

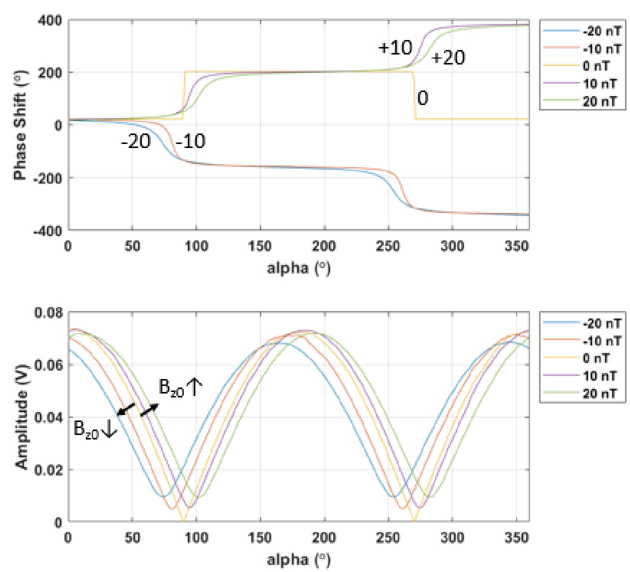

Fig. 2: Measured cross-axis projection error

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Triaxial OPMs: Next generation of wearable MEG?

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[2] *QuSpin Inc., Louisville, CO, USA*

MEG systems based on SQUID sensors typically measure one component of the neuromagnetic field, due to the complexity of the required geometry of flux transformers. However, newly available commercial OPMs offer the possibility to measure a complete triaxial magnetic field at multiple locations across the scalp. Here, we aimed to test the suitability of such sensors for MEG.

A simulated MEG system based on triaxial sensors (Figure 1a) showed that vector measurement might be particularly useful for studying the infant brain: As the brain of an infant is closer to the sensors than that of an adult, a radial-only system results in gaps in coverage. However, a triaxial array fills these gaps, providing more uniform coverage. In addition, previous work suggests that triaxial measurements would be advantageous for rejecting interference [1].

Triaxial wearable MEG devices are now commercially available, and using 4 of these sensors, we tested their suitability to measure biomagnetic signals. Figure 1b shows the magnetic field from the human heart, measured at multiple locations above the chest. Figure 1c shows 4 triaxial sensors used to measure the magnetic field from the brain (the field generated by a burst of beta activity in the left primary somatosensory cortex). In both cases sensors showed excellent sensitivity to the biomagnetic field, across all three available axes.

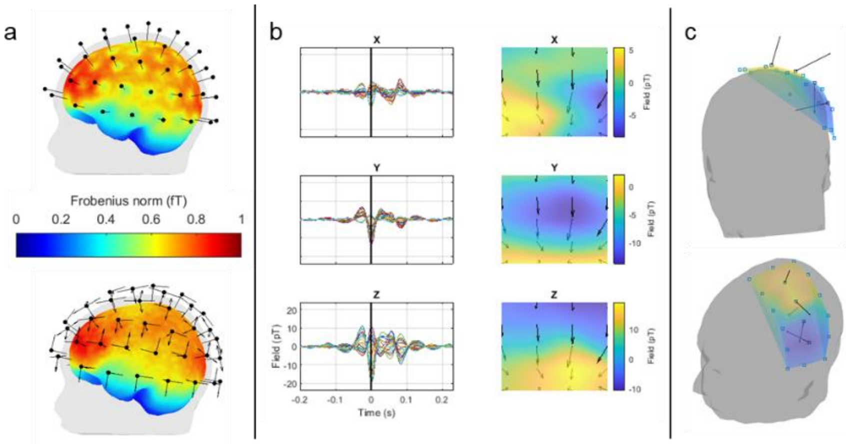

Figure 1: a) A simulated triaxial array (bottom) results in more uniform coverage, compared to a radial-only array (top). b) MCG signals measured with triaxial sensors. c) Vector neuromagnetic fields from 4 triaxial OPMs placed over left primary sensorimotor cortex.

These data show clearly the utility of triaxial sensors for MEG, which offer similar performance to the conventionally available dual axis OPMs, but with the added benefit of an additional measurement. We believe triaxial OPMs will show utility in scanning infants (due to improved coverage) and will offer improved rejection of interference.

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A pulsed vector optically pumped magnetometer operating in the SERF regime

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We describe a vector optically pumped magnetometer operating in the SERF regime. By applying short pulses of 795 nm light using a high-power multimode laser diode (2.5 W), we generate spin polarization in a hot ^{87}Rb vapor. We monitor the free precession of the spin polarization by observing the Faraday rotation of a linearly polarized 780 nm probe beam (TA pro, Toptica Photonics AG) collinear to the pump beam [1]. One or multiple components of the magnetic field can be detected by rotating the spin polarization using magnetic field pulse sequences of different designs produced by an H-bridge circuit [2].

Fig. 1A shows a 5-ms pulse sequence used to detect B_y with pump/probe along z-axis. A 25 µs π/2-pulse along y-axis is used to rotate the initial spin polarization from z-axis to x-axis. A π-pulse also along the y-axis is used in the midway of the sequence to rotate the polarization around the y-axis to facilitate demodulation of the probe rotation signal with a bipolar waveform. The demodulated signal is linear with respect to small changes of B_y (Fig. 1B). Sensitivity of ~40 fT/rHz has been achieved (Fig. 1C). We are currently working to reduce the technical noise of the magnetometer.

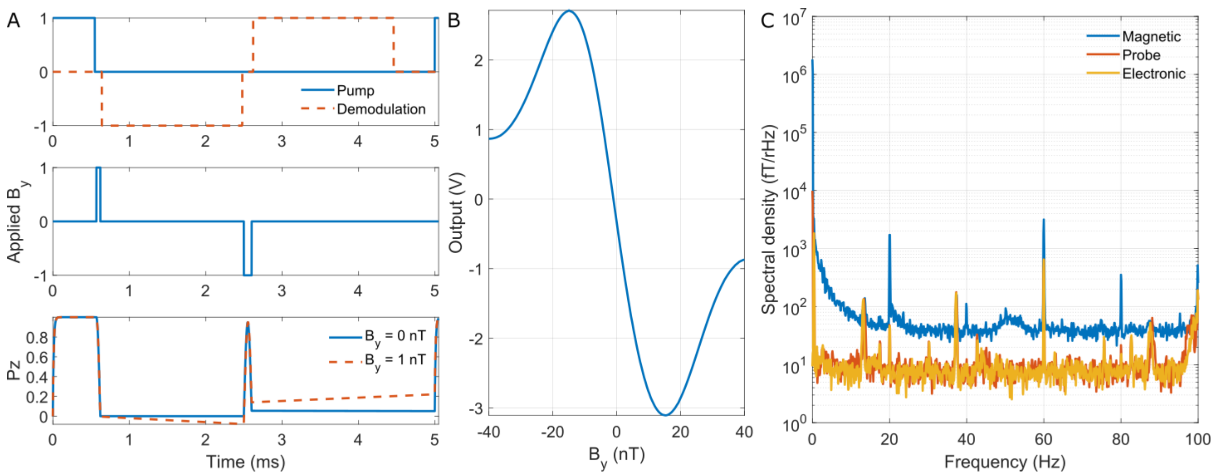

Fig. 1 A: Pulse sequence for measuring B_y. Top two panels illustrate the pump signal, demodulation waveform and the magnetic field pulses along the y-axis while the bottom panel shows the time-evolution of the spin polarization along pump/probe beams. **B:** Measured signal after demodulation as a function of B_y. **C:** Noise spectral density. Magnetic noise is shown as well as the estimated noise contributions from the probe beam and electronics.

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Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Feedback and bandwidth in self-oscillating and radio-frequency OPMs

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The instantaneous response in atomic Larmor frequency to changes in magnetic field is a significant advantage of OPMs and can be exploited for high bandwidth field measurements using free-induction (FID) readout [1,2]. However, in OPM schemes which exploit resonant modulation to increase signal amplitude and duty cycle, the response to field changes depends non-trivially on feedback latency and atomic relaxation rate [3]. Additionally, in tuned radio-frequency OPMs [4], response to variation in signal phase and frequency has a strong dependence on atomic relaxation, implying a trade-off between the sensitivity and bandwidth of these devices.

We examine the implementation of low-latency digital feedback in modulated OPM systems, including data showing the resulting bandwidth, sensitivity limits and common-mode noise rejection. We discuss digital design optimization and applications for portable OPM systems exploiting these concepts.

This work is supported by the EPSRC Quantum Technology Hub in Sensors and Metrology, the UK Defence Accelerator and Innovate UK.

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