Strathclyde Innovation Symposium on Optically Pumped Magnetometers

September 25th-26th 2018, Ross Priory

Programme and travel information

Welcome

We are delighted you are joining us for this innovation symposium on optically pumped magnetometers. This one-off two-day event brings together global leaders in OPM research and commercialization with a wide range of academic and industrial developers in order to share ideas and foster new collaborations. The symposium is made possible through funding for OPM development through the UK National Quantum Technologies Hub in Sensors and Metrology

The symposium venue is Strathclyde University's conference facility at Ross Priory on the southern shore of Loch Lomond and we remain hopeful that western Scotland's unpredictable autumnal weather will allow everyone to enjoy this scenic location (although we also advise you to bring a coat).

Ross Priory

The history of Ross Priory began with the Buchanan Clan during the 11th century, with a dwelling known to have existed on the site from as early as 1693. It is reported that in 1745 the Leith-Buchanans were cursed by the Marquess of Tullibardine, who, in the aftermath of the Battle of Culloden, asked James Leith- Buchanan, 5th of Ross, for shelter at the Priory but was instead betrayed and given over to King George's men. Tullibardine cursed them with the utterance: "There will be Murrays on the Braes of Atholl land when there's ne'er a Buchanan at the Ross." The Marquess's curse came to pass when, in 1925, the Leith-Buchanan's male line finally died out and the house was leased to Major George J.H. Christie, a veteran of World War I, remaining in the family's possession until shortly after the Major's death. Christie was responsible for the development and cultivation of the Priory's surrounding gardens. The Priory was sold to the University of Strathclyde in 1971. Although the term "Priory" implies some ecclesiastical provenance, this is not the case, being simply a 19th century romantic affectation. The current building was designed in 1812 by Dunblane-born architect James Gillespie Graham (1776-1855) as an extensive remodelling of the site's existing farmhouse.

Sir Walter Scott was known to have visited several times and wrote a number of letters from the house, and is said to have written at least part of 'The Lady of the Lake' and 'Rob Roy' here.

Ross Priory comprises approximately 200 acres of land and includes a formal garden, parkland, a burial ground and golf course. Ross Priory is situated on the southern shore of Loch Lomond some 25 miles north-west of the centre of Glasgow. Conic Hill 1,175' (358 m) rises above Balmaha about 4 km across the loch, and beyond stand Ben Lomond 3,196' (974 m) and Ben Vorlich 3,054' (931 m). The Highland Boundary Fault runs through the north side of Conic Hill.

Schedule

Tuesday September 25th

9:00 am	Coach transfer departs Collins Street, central Glasgow
9:45 am	Coach transfer departs Glasgow Airport
10:30 am	Arrive Ross Priory, registration & welcome to venue

11:00 am	**Session 1**	**Developments in high-sensitivity magnetometry**
	Chair	Dr. Paul F. Griffin, Strathclyde University
11:00 am	**Dr. Volkmar Schultze, Leipzig IPHT** *Optically pumped magnetometers for operation at Earth's field strength*	
11:20 am	**Prof. Peter Schwindt, Sandia National Laboratory** *Magnetic Source Imaging Using a Pulsed Optically Pumped Magnetometer Array*	
11:40 am	**Cameron Deans, University College London** *A New Multi-Purpose Quantum Imaging Platform: Atomic Magnetometers and Induction Imaging*	
12:00 pm	**Dr. Stuart Ingleby, University of Strathclyde** *Single-beam double-resonance vector magnetometry*	

12:30 pm — Lunch

1:30 pm — **Invited speaker: Dr. Michael S. Larsen, Northrop-Grumman**
Spin Polarized Atomic Sensors – Developing Gyroscopes and Magnetometers

2:30 pm — **Invited speaker: Dr. Vishal Shah, QuSpin Inc.**
Optically Pumped Magnetometers: From Laboratory to Real-World

3:30 pm — Coffee & posters

4:30 pm	**Session 2**	**High-sensitivity magnetometry in medicine**
	Chair	Dr. Stuart Ingleby, Strathclyde University
4:30 pm	**Prof. Kasper Jensen, University of Nottingham** *Magnetocardiography on an isolated animal heart with a room-temperature optically pumped magnetometer*	
4:50 pm	**Dr. Mark Bason, University of Sussex** *Towards magnetospinography with optically-pumped magnetometers*	
5:10 pm	**Prof. Ben Varcoe, University of Leeds** *Magnetocardiography Development at Creavo Medical Technologies*	
5:30 pm	**Niall Holmes, University of Nottingham** *A multi-channel OPM-MEG system: from construction to application*	

6:00 pm	Poster session, Scott Room (1st floor)
7 pm	Symposium dinner
9:30 pm	Coach transfer to accommodation

Wednesday September 26th

8:15 am	Coach transfer to Ross Priory
9 am	**Invited speaker: Prof. Svenja Knappe, University of Colorado** *Microfabricated Optically-Pumped Magnetometers for Non-Invasive Brain Imaging*
10 am	**Invited speaker: Rahul Mhaskar, Ph.D., Geometrics Inc.** *Miniature Scalar Atomic Magnetometers: Advances and Applications*
11 am	Coffee
11:30 am	**Invited speaker: Thomas W. Kornack, Ph.D., Twinleaf LLC** *Finite-field high-sensitivity sensors*
12:30 pm	Lunch
1:30 pm	Optional putting/walk/posters/coffee*
3:30 pm	**Session 3 OPM technologies and applications** Chair Prof. Erling Riis, Strathclyde University
3:30 pm	**Dr. Terry Dyer, University of Strathclyde** *Microfabricated Vapour Cells for Atomic Magnetometry*
3:50 pm	**Dr. Kamyar Mehran, Queen Mary, University of London** *Improving the life-cycle and safety of the lithium-ion battery packs in electric vehicles using quantum magnetometers*
4:10 pm	**Dr. Michael Tayler, University of Cambridge** *Atomic Magnetometry for Nuclear Magnetic Resonance*
4:30 pm	**Dr. Ole Kock, Teledyne e2v** *Quantum Technologies at Teledyne e2v*
4:50 pm	Closing remarks
5:00 pm	Coach departure from Ross Priory
5:30 pm	Coach returns to Glasgow Airport
6:00 pm	Coach returns to central Glasgow

* Ross Priory has a 9-hole golf course and putting green. Balls and putters are available to borrow on the day.

Travel information

Getting to Glasgow

Strathclyde University Physics department is located in the John Anderson Building, 107 Rottenrow East, G4 0NG. The symposium will be held at the University's Ross Priory conference venue (G83 8NL), located approximately 20 miles from the city on the banks of Loch Lomond.
By rail: Glasgow Central and Queen Street Stations are located in the city centre, within 20 minutes' walk of Strathclyde University. Incoming trains from the south mainly terminate at Central Station, which has a journey time of approximately 5 hours from London Euston.

By air: Glasgow Airport is connected to the city centre by a frequent bus service (no. 500) with a journey time of 30 minutes. The £12 return fare can be paid by cash or card at the bus stop. Edinburgh Airport is approximately 1¼ hours from Glasgow city centre by bus, see https://www.citylink.co.uk/citylinkair.php for more details.

Getting to and from Ross Priory

Coach transfer (Allander Travel) is organised between the city centre, airport and symposium venue. The outward journey on Tuesday 25th will depart Collins Street (G4 0NL) at 9:00 am, calling at Glasgow Airport (pick up point located on Bute Road, one of the locals will meet you at the main arrivals hall) at 9:45 am and continuing to Ross Priory. The return journey will depart Ross Priory at the end of the symposium (5 pm Wednesday 26th), calling at Glasgow Airport at 5:30 pm, arriving back at Collins Street at 6:00 pm. Coach transfer is included in symposium registration. The organisers ask you to confirm (if you have not already done so) whether you require a coach seat, and if so, your boarding location (city centre or airport). Places are not limited but we would like to ensure that we have all aboard!

Delegates arranging their own transport will find ample car parking at Ross Priory, which is located off the A811 Drymen to Balloch road, G83 8NL.

Accommodation

Accommodation is booked for all delegates for Tuesday 25th. This consists of bed and breakfast in either the Buchanan Arms Hotel, Winnock Hotel or Drymen Inn, all of which are located in Drymen. Coach transfer is organised between Ross Priory and these hotels following dinner on Tuesday 25th. A return transfer will depart Drymen at 8:15 am on Wednesday 26th.

Lunch & Dinner

Buffet lunches will be provided on the 25th and 26th with a range of vegetarian and non-vegetarian options. The symposium dinner will be held at Ross Priory on Tuesday 25th. If you have not already done so, please contact the organisers directly with any specific dietary requirements.

Invited Speakers

Dr. Michael S. Larsen, Northrop-Grumman
Dr. Michael Larsen received his Ph.D. in physics from the University of Wisconsin, Madison in 2007. He is currently the lead physicist for quantum sensing in the Advanced Position, Navigation, and Timing Systems group at Northrop Grumman in Woodland Hills, California. Dr. Larsen's focus is the application of atomic physics to the development of high performance, low size, weight and power sensors. His primary project has been the development of the nuclear magnetic resonance gyroscope under both DARPA and internal funding. In addition he is also working on a compact atomic vector magnetometer, a scalar and differential scalar magnetometer, an optical cavity readout accelerometer, a cold atom interferometer accelerometer, and an atomic clock. Dr. Larsen holds 17 patents in the field of atomic sensors and related technologies, as well as 6 refereed publications. Dr. Larsen received Engineering Achievement Awards in 2009 and 2018 from the San Fernando Valley Engineers' Council as well as the President's Leadership Award in 2013 from Northrop Grumman for his role as the principal investigator on the Nuclear Magnetic Resonance Gyroscope and other quantum sensing research and development teams.

Spin Polarized Atomic Sensors – Developing Gyroscopes and Magnetometers
Northrop Grumman has been developing spin polarized atomic sensors since 1967. The work started with the development of a Nuclear Magnetic Resonance Gyroscope (NMRG) using then new techniques of spin exchange optical pumping and co-magnetometry. Offshoot technologies soon followed including magnetometers and atomic clocks leveraging the common supporting technologies. This presentation will describe the development history, underlying physics of operation, common supporting technologies, and current status of the NMRG and related offshoot technologies.

Dr. Vishal Shah, QuSpin Inc.
Dr. Vishal Shah is currently the Founder and Chief Scientist at QuSpin. Prior to founding QuSpin in 2012, Dr. Shah worked as a Physicist at Symmetricom (now Microchip) from 2009 to 2012 on developing a compact cold atom clock. Dr. Shah received a Ph.D. in AMO physics for his work on chip-scale atomic clocks and magnetometers at NIST/University of Colorado in 2007. Subsequent to graduate studies, Dr. Shah worked as a postdoctoral researcher in Romalis group at Princeton where his research focused on improving the performance of atomic devices using quantum non-demolition measurements.

Optically Pumped Magnetometers: From Laboratory to Real-World
In my talk, I will give an overview of the work at QuSpin on developing commercial grade optically pumped magnetometers (OPM). Specifically, I will discuss the current status of our zero-field and scalar OPM technology, and our view on the technical potential of this technology in the next five years. I will also share our experience in taking this technology from laboratory to commercial domain.

Prof. Svenja Knappe, University of Colorado, Boulder
Svenja Knappe received her Ph.D. in physics from the University of Bonn, Germany in 2001 with a thesis on miniature atomic magnetometers and atomic clocks based on coherent-population trapping. For 16 years, she worked at the National Institute of Standards and Technology (NIST) in Boulder CO, developing chip-scale atomic sensors. She is now an Associate Research Professor at the University of Colorado and her research interests include microfabricated atomic sensors. She is also a co-founder of FieldLine Inc.

Microfabricated Optically-Pumped Magnetometers for Non-Invasive Brain Imaging
We present our ongoing effort in developing imaging systems with microfabricated optically-pumped magnetometers (μOPMs). By use of microfabrication technologies and simplification of optical setups, we aim to develop manufacturable sensors of small size and low power. Our zero-field μOPMs require a shielded environment but reach high sensitivities of less than 10 $fT/Hz^{1/2}$. Target applications lie in the field of non-magnetic brain imaging, specifically magnetoencephalography (MEG). The attraction of using these sensors for non-invasive brain imaging comes from the possibility of placing them directly on the scalp of the patient, very close to the brain sources. We have built several multi-channel test systems to validate the prediction of very high signal-to-noise ratios in standard MEG paradigms.

Dr. Thomas W. Kornack, Chief Scientist, Twinleaf LLC
Dr. Kornack is an expert in the design, fabrication and operation of magnetometers and gyroscopes, with over seven years of research in the field and authorship on groundbreaking publications. During graduate and postdoctoral work at Princeton University, he has worked on many important projects, including the development of the first SERF magnetometers. For his dissertation, he built a high-performance co-magnetometer to probe fundamental laws of physics and for use as a sensitive gyroscope. In 2007, Dr. Kornack founded Twinleaf to develop and commercialize these sensors for use in a wide variety of applications. Twinleaf's core technological basis is derived from his extensive experience building the world's most sensitive magnetic field sensors.

Finite-field high-sensitivity sensors
Modern alkali metal sensors achieve both high performance and smaller size thanks to breakthroughs in suppressing the effects of spin-exchange collisions among atoms, both at zero field and now at finite field. While zero field SERF magnetometers with less than 10 $fT.Hz^{-1/2}$ sensitivity are now an established technique, achieving the same performance at finite field is an exciting new development, potentially obviating the need for costly magnetic shielding. I review the history of this field and discuss commercial development of sensors at Twinleaf.

Rahul Mhaskar, Ph.D, Geometrics Inc.

Dr. Rahul Mhaskar is Vice President for Research and Development at Geometrics, a manufacturer of geophysical instrumentation with worldwide presence. He earned his Ph.D. in Applied Physics from the University of Michigan under the direction of Prof. Georg Raithel. After a brief stint at Harvard University, he joined the Time and Frequency Division at the National Institute of Standards and Technology in Boulder, CO as a postdoc, working with Dr. John Kitching and Dr. Svenja Knappe on Chip-Scale Atomic Magnetometers. While at NIST, he developed microfabricated fiber-coupled SERF magnetometers and was among the first researchers to demonstrate the magnetoencephalography using these uncooled sensors. Subsequently, he took a position at Geometrics to lead the development of highly precise miniature scalar magnetometers for geomagnetic measurements. Using these sensors, he demonstrated measurement of magnetocardiography in a commercial environment. Having overseen the development of miniature magnetometers from concept to a manufactured product, he is now focused on applying their low payload signature capability to geomagnetic surveys using autonomous platforms such as drones and autonomous underwater vehicles.

Miniature Scalar Atomic Magnetometers: Advances and Applications

Scalar magnetometers are used to make very precise measurements of small deviations in the Earth's field to detect a wide variety of objects ranging from pipes and unexploded ordnance (UXO) to submarines. Atomic magnetometers are typically used as the sensor of choice in measuring the magnitude of the Earth's magnetic field through the Larmor precession of atomic spins.

Over the past five decades, scalar atomic magnetometry technology has relied on radio frequency (RF) magnetic fields to drive the Larmor precession and RF discharge lamps as the light source to detect the precession. Within the past ten years, Vertical Cavity Surface Emitting Laser (VCSEL) technology, developed for chip scale atomic clocks, has enabled significant miniaturization of the atomic magnetometers with commensurate decrease in power consumption. The miniature magnetometers now allow integration of these sensors in numerous applications where earlier, the size and weight of the lamp-based sensors precluded their use.

In this talk, I present an overview of scalar atomic magnetometer development at Geometrics. I further present the application of these sensors in geophysical measurements and beyond, touching upon magnetocardiography, non-destructive testing of conductive bulk materials, and infrastructure monitoring.

The convergence of a number of technologies including the development of autonomous platforms, heuristic analyses of large data sets, and ubiquitous computing opens up substantially new application areas for the miniature atomic magnetometers with seemingly unending possibilities.

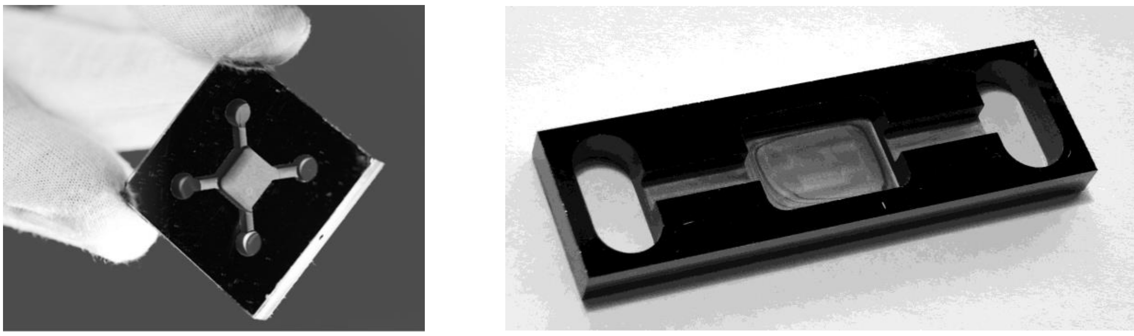
Abstracts

Optically pumped magnetometers for operation at Earth's field strength

Volkmar Schultze[1], Rob IJsselsteijn[2], Christian B. Schmidt[1], Gregor Oelsner[1], Florian Wittkämper[1], Ronny Stolz[1]

[1] Leibniz Institute of Photonic Technology (Leibniz-IPHT), Albert-Einstein-Straße 9, 07745 Jena, Germany
[2] Supracon AG, An der Lehmgrube 11, 07751 Jena, Germany

The development of Optically Pumped Magnetometers (OPM) at Leibniz-IPHT especially intends to address applications such as geophysical prospection or biomagnetic measurements without magnetic shielding. Thus, the magnetometers have to be operable in Earth's field without compromises in dynamic range and magnetic field resolution. These applications require the use of multiple sensor elements rather than a single OPM. As a consequence, assemblies of multiple alkali vapor cells with stable and mutually referenced properties on a single chip are used, thus also enabling new operational modes and complex magnetic-field characterization.
With advanced micro-systems technologies adapted from earlier NIST developments [1] and improved at the Leibniz IPHT [2,3] long-term stable OPM cell assemblies using micro-structured silicon substrates enclosed with anodically bonded glass plates are produced. The Figure shows two examples of OPM cell arrays used herein.



Integrated cesium vapor cell assemblies with common cesium reservoir in 4 mm thick silicon substrates.
Left: Four locally separated 4 mm wide magnetometer cells;
Right: Gradiometer consisting of two wide magnetometer cells.

In order to achieve good magnetic-field sensitivities despite the small cell volume of only several ten cubic millimeters, new operational modes have been developed as an alternative to spin-exchange relaxation-free (SERF) operation as this method is not operable in magnetic fields of several 10µT such as the Earth's field. Using strong detuned pumping, light-narrowing (LN) is achieved, which reduces the shot-noise limited magnetic-field resolution B_{sn} achieved with the small cells from 200 fT/√Hz in the conventional M_x mode down to 40 fT/√Hz in the LN mode [4]. The combination of the signals of appropriately operated identical cells can improve the signal quality further. Thereby, we introduced the new light-shift dispersed M_z (LSD-Mz) mode for which the shot-noise limited resolution, using the same OPM cells, can be reduced down to about 10 fT/√Hz providing a bandwidth from DC to several hundred Hertz [5].
With appropriately adapted vapor cell layouts and operational modes various applications are addressed, as – for example – biomagnetic characterization and imaging at humans and animals.

[1] L. Liew et al., Appl. Phys. Lett. **84**, 2694 (2004).
[2] S. Woetzel et al., Rev. Sci. Instr. **82**, 033111 (2011).
[3] S. Woetzel et al., Surface & Coatings Technology **221**, 158 (2013).
[4] T. Scholtes et al., Optics Express **20**, 29217 (2012).
[5] V. Schultze et al., Sensors **17**, 561 (2017).

Magnetic Source Imaging Using a Pulsed Optically Pumped Magnetometer Array

Amir Borna[1], Tony R. Carter[1], Paul DeRego[2], Conrad D. James[1], Peter D. D. Schwindt[1]

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[2] Kansas City National Security Campus, 2450 Alamo Ave SE, Albuquerque, NM 87106

We have developed a pulsed optically pumped magnetometer (OPM) array for detecting magnetic field maps originated from an arbitrary current distribution. The presented magnetic source imaging (MSI) system features 24 OPM channels, has a data rate of 500 S/s, a sensitivity of 0.8 $pT/\sqrt{Hz}$, and a dynamic range of 72 dB. We have employed our pulsed-OPM MSI system for measuring the magnetic field map of a test coil structure. The coils are moved across the array in an indexed fashion to measure the magnetic field over an area larger than the array. The captured magnetic field maps show excellent agreement with the simulation results. Assuming a 2D current distribution, we have solved the inverse problem, using the measured magnetic field maps, and the reconstructed current distribution image is compared to that of the simulation.

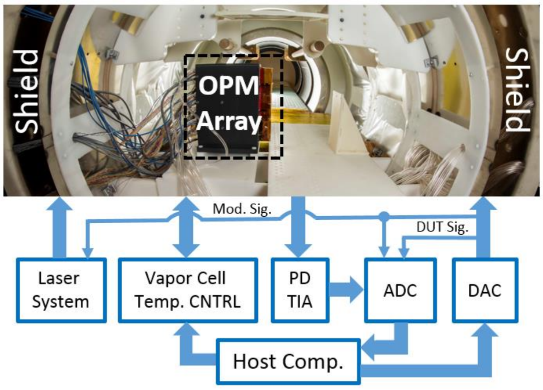

Fig. 1. The magnetic sensor array inside the three-layer magnetic shield. PD TIA: transimpedance amplifiers of the photo diodes; ADC: analog-to-digital-converter; DAC: digital-to-analog-converter; device under test (DUT) Sig.: the signal driving the device under test; Mod. Sig.: the control signal modulating the laser system, the bias field, and the polarizing magnetic field.

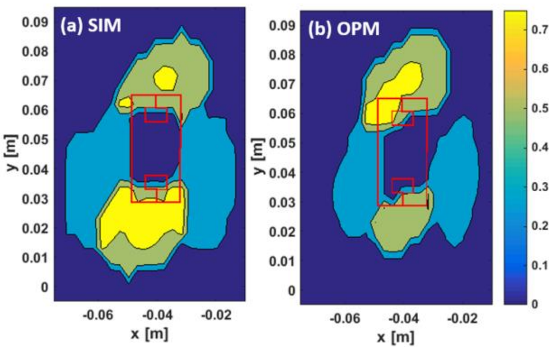

Fig. 2. Current distribution imaging using simulated (a) and measured (b) magnetic fields. The coil structure is overlaid on top of the constructed current density vectors.

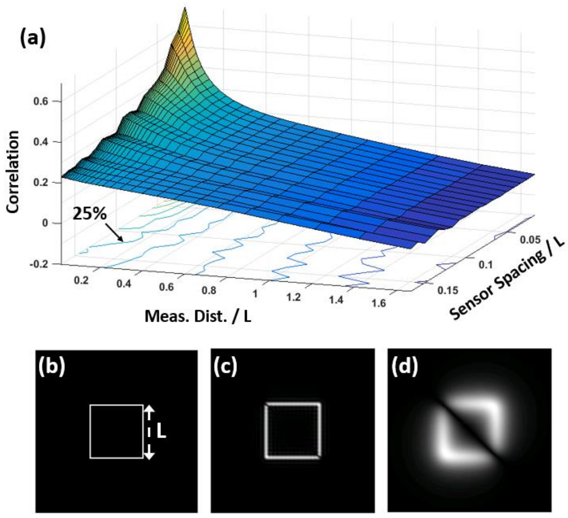

Fig. 3. The dependency of the constructed current density image quality on the measurement distance (z_0) and array's sensor spacing normalized to the length of the side, L: a) the correlation between the original current carrying trace and the constructed current density image; b) the 1-cm wide original current carrying trace with a side length of 30 cm; c-d) the constructed current density image for a correlation of 70 % and 25 % respectively.

A New Multi-Purpose Quantum Imaging Platform: Atomic Magnetometers and Induction Imaging

C. Deans, L. Marmugi, F. Renzoni
Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT

We present a non-invasive sensing and imaging system based on atomic magnetometers (AMs) operating in magnetic induction tomography (MIT) modality. An AC magnetic field induces eddy currents in the sample of interest, probing its conductivity. The response is mapped with radio-frequency AMs. Their superior performance - in terms of sensitivity, tunability, unshielded and room-temperature operation - makes RF AMs the ideal choice for moving the device to outdoor applications. In particular, their sensitivity allows detection and imaging of non-magnetic, low-conductive targets. The possibility of arbitrarily choosing the operating frequency allows penetration of concealing barriers and remote detection, potentially up to several kilometres and underwater. This paves the path towards a new generation of non-invasive, non-destructive and ultra-sensitive imaging platforms for multi-purpose applications.
In this talk, we will report on the ongoing research at UCL aimed at the application of the new sensing platform to non-destructive evaluation of materials, industrial monitoring, defence and security, and biomedical imaging. We will show demonstrations of: imaging of metallic and non-metallic targets; penetration of thick barriers; 2x2 array operation; and remote detection and localisation in air and underwater. The most recent developments which led the to the record sensitivity of 100 fT/Hz$^{1/2}$, with a single sensor in an unshielded environment, and the first application of machine learning to AMs and electromagnetic induction imaging will be presented. Finally, perspective towards the realization of a conductivity map of the heart for the diagnosis of atrial fibrillation will be discussed.

Single-beam Vector Magnetometry Exploiting Orientation-Phase Effects in a Double-Resonance Sensor

Stuart J. Ingleby[1], Carolyn O'Dwyer[1], Paul F. Griffin[1], Aidan S. Arnold[1] and Erling Riis[1]

1. Department of Physics, SUPA, Strathclyde University, 107 Rottenrow East, Glasgow

Conventional double-resonance magnetometry yields a scalar measurement of the static field magnitude B_0, through measurement of the resonant response to a modulation field B_{RF} at a frequency ω_{RF} close to the atomic Larmor frequency ω_L [1]. We present detailed experimental data and atomic polarisation models for the observed amplitude and phase of double-resonance magnetometer signals under arbitrary orientations of B_0 [2]. Further, we demonstrate a unique mapping between the phase of the first- and second-harmonic signal components and B_0 orientation, allowing determination of the field vector from demodulated on-resonance data.

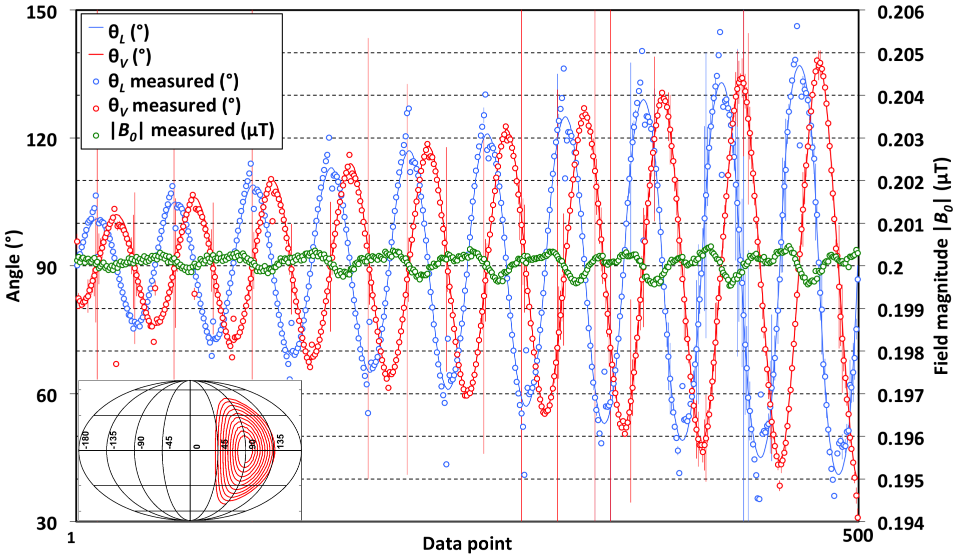

Fig. 1 Measured and set magnetic field magnitude and orientation over a wide range of range of B_0 orientations. The point of best angular resolution is measured at $|B_0|$ = 199.8445(17) nT, θ_V = 100.986(27)°, θ_L = 100.986(27)°. The inset figure shows the contour described by B_0 orientations around the axis of maximum magnetometer sensitivity.

We discuss the potential applications of this technique and the current limitations on resolution and bandwidth, as well as hardware developments for portable unshielded systems.

This work is supported by the EPSRC Quantum Technology Hub in Sensors and Metrology [3].

References

[1] A. L. Bloom, *Principles of Operation of the Rubidium Vapor Magnetometer*, Applied Optics **1**, 61 (1962)

[2] S. J. Ingleby, C. O'Dwyer, P. F. Griffin, A. S. Arnold, and E. Riis, *Orientational effects on the amplitude and phase of polarimeter signals in double-resonance atomic magnetometry,* Phys. Rev. A **96**, 013429 (2017)

[3] www.quantumsensors.org

Magnetocardiography on an isolated animal heart with a room-temperature optically pumped magnetometer

Kasper Jensen[1,*], Mark Alexander Skarsfeldt[2], Hans C. Stærkind[1], Jens Arnbak[1], Mikhail V. Balabas[1,3], Søren-Peter Olesen[2], Bo Hjorth Bentzen[2], Eugene S. Polzik[1]

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Optically pumped magnetometers are becoming a promising alternative to cryogenically-cooled superconducting magnetometers for detecting and imaging biomagnetic fields. Magnetic field detection is a completely non-invasive method, which allows one to study the function of excitable human organs with a sensor placed outside the human body. For instance, magnetometers can be used to detect brain activity or to study the activity of the heart. We have developed a highly sensitive miniature optically pumped magnetometer based on cesium atomic vapor kept in a paraffin-coated glass container. The magnetometer is optimized for detection of biological signals and has high temporal and spatial resolution. It is operated at room- or human body temperature and can be placed in contact with or at a mm-distance from a biological object. With this magnetometer, we detected the heartbeat of an isolated guinea-pig heart, which is an animal widely used in biomedical studies. In our recordings of the magnetocardiogram, we can in real-time observe the P-wave, QRS-complex and T-wave associated with the cardiac cycle. We also demonstrate that our device is capable of measuring the cardiac electrographic intervals, such as the RR- and QT-interval, and detecting drug-induced prolongation of the QT-interval, which is important for medical diagnostics.

Reference: K. Jensen et al. *Magnetocardiography on an isolated animal heart with a room-temperature optically pumped magnetometer.* arXiv:1806.10954 (2018)

Towards magnetospinography with optically-pumped magnetometers

Dr. Mark Bason, University of Sussex

The last decades have seen significant attention in measurements of bio-magnetic activity from the heart and brain. Extending these studies to include the spinal cord will offer significant opportunities for clinical studies in a range of diseases and conditions. In this talk, I will look at the perspectives for measurements of the spinal cord with OPMs and discuss their advantages over SQUID-based systems and equivalent electrical measurements. I will discuss our plans at Sussex for two such measurements: the evolution of pathological markers following an early multiple sclerosis attack and estimations of central sensitisation in patients with neuropathic pain.

Magnetocardiography Development at Creavo Medical Technologies

Ben Varcoe, University of Leeds and Creavo Medical Technologies

Cellular action potentials originating in myocardial cells generate electrical activity in the heart, but they also create magnetic fields. Changes in perfusion (blood supply) affect the action potential leading to commensurate changes in the magnetic field. Mapping the cardiac magnetic field therefore creates a signal that reflects the extent of change in action potential within the heart. Since both the ECG and MCG are detecting signals generated by the same electrical activity of the heart, MCG can be considered the magnetic equivalent of an ECG. However, the MCG has a number of key advantages, with one example being that the magnetic field is not diffused or dispersed by tissue. While the magnetic fields are extremely small a magnetic field map is nevertheless capable of differentiating between normal and abnormal cardiac behaviour and has been shown in clinical trials to provide useful and different information than ECG over a range of cardiac conditions. The reason for this is that a localised problem in the heart, such as necrosis or ischaemia, disrupts the magnetic field impacts and distorts the entire magnetic field and thus has a significant effect on the MCG scan. A healthcare professional that is familiar with a normal scan might therefore be able to identify different cardiac conditions by studying the resultant magnetic maps, waveforms and numerical data produced. However, given that there are a number of ways that the magnetic field of the heart can be impacted by changes at a cellular level, the easiest diagnosis to make is “normal”. This is unusual in medicine where the aim is normally to find the problem, however, in an emergency department with a patient presenting with a potentially life threatening condition, the diagnosis of “normal” saves stress, time and money. An immediate and valuable application is to use magnetocardiography to positively filter out the “worried well” in the emergency department. However developing a device that is useful in this context is tricky, because it needs to be rapidly and easily deployed at the patient’s bedside by someone with minimal training. It needs to be light, mobile and robust. It therefore needs to be both sufficiently sensitive and sufficiently immune to the types of electrical and mechanical noise that are present in a noisy emergency department to be able to deliver a medically valid response. This is an extremely challenging environment for precision sensors, shielding is impossible and the beds are typically made of ferromagnetic material. A wide range of sensors have been used for magnetocardiography, including induction coil, SQUID, atomic physics and solid state sensors, all of which are sufficiently sensitive. The difficulty is in making them immune to noise. Hence, the main aim of our research over the last 15 years has been the development of sensor arrangements and signal processing solutions that enables magnetocardiography to be performed in such environments. This work has been commercialised by a start-up called Creavo Medical Technologies and we now have devices in more than a dozen locations in the UK, Germany and USA collecting patient data in emergency departments and thousands of patient scans. This talk will discuss the challenges and some of the elements that have gone into developing a solution.

A multi-channel OPM-MEG system: from construction to application

Niall Holmes[1], James Leggett[1], Elena Boto[1], Ryan M Hill[1], Gillian Roberts[1], Tim M Tierney[2], Vishal Shah[3], Rebeccah Slater[4], Gareth R Barnes[2], Richard Bowtell[1] and Matthew J Brookes[1]

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Magnetoencephalography (MEG) is a non-invasive measure of brain function with high temporal and spatial resolution. Traditional MEG devices are cooled with liquid helium and require subjects to remain still within a fixed sensor array limiting the subject groups which can be studied, and experiments which can be performed. Recently we have shown a MEG device employing optically pumped magnetometers (OPMs) which allows high quality data to be collected during large subject motions [1,2].

The QuSpin OPM has a noise floor of 15 fT/√Hz but also a narrow dynamic range of ±1.5 nT: any movements through the spatially inhomogeneous remnant magnetic field inside a magnetically shielded room (MSR) quickly saturates measurements. To address this issue a field compensation system was constructed to null this field and allow large subject movements [2]. The coil currents are controlled by a reference array of OPMs allowing for reduction of the dominant component of the remnant field by a factor of ~45 and dominant gradient by a factor of ~13.

The positions and orientations of the OPMs with respect to the subject's brain are required for source reconstruction. This information is currently obtained using subject-specific, 3D printed scanner-casts which are both bulky and expensive to produce on a subject by subject basis. As a first step towards more generic designs we have employed adapted bicycle helmets where sensor locations can be obtained via an X-Ray of the helmet co-registered to a digitisation of the subject's head. Preliminary results using these helmets show a robust neural response can be observed in three subjects aged 2, 5 and 24. This is a crucial first step in realising the potential of OPM-MEG to investigate the developing brain. The incorporation of the system with virtual reality headsets is also being investigated to provide a more naturalistic environment in which to study the brain.

[1] Boto et al., Nature 2018. [2] Holmes et al., NeuroImage 2018.

Improving the life-cycle and safety of the lithium-ion battery packs in electric vehicles using quantum magnetometers

Dr. Kamyar Mehran, Queen Mary University of London

Online condition monitoring of the xEV battery module by far is a difficult problem. The monitoring is crucial to increase the life-cycle of the battery packs and eliminate the possibility of batteries overheating and causing fires, which remains an important consumer concern. The direct measurement of the critical battery cell parameters, i.e. state-of charge (SoC), state-of-health (SoH), and temperature, has not yet become possible and all the sophisticated estimation techniques suggested is hard to be practically embedded in the battery management system (BMS). We propose to use an emerging quantum sensor technology, i.e. quantum magnetometer array, to measure the current flow through EV batteries. With the help of the array, we characterise current irregularities during ion transfer for charging/discharging and generate images to be encoded in the BMS using novel data processing system. This new generation of BMS will maintain an accurate and timely estimate of the critical parameters to effectively increase the life-cycle of the battery packs and provide the required safety for specially battery electric vehicles.

Atomic magnetometers for nuclear magnetic resonance (NMR)

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Optically pumped alkali-metal magnetometers (OPMs) that reach sensitivities of <20 femtotesla/$Hz^{1/2}$ are easily capable of detecting the magnetic field produced by polarized ^{1}H, ^{13}C and several other magnetically active nuclei in matter. Over the past 10-15 years this has stimulated the development of optical magnetometers for nuclear magnetic resonance spectroscopy (NMR) and magnetic resonance imaging (MRI), two indispensable tools for analyzing the internal structure, chemistry and dynamics of soft matter.

What is the future of OPMs in NMR? NMR spectroscopy has trended over its 70+ year history towards very strong magnetic fields of 10-20 tesla. In these fields, induction-coil detection of NMR signals is many orders of magnitude more sensitive than the best OPMs, and resolved chemical shifts can be used for molecular identification/quantitation in mixtures containing hundreds of different compounds.

To address the above question, my short talk will highlight the value of OPMs in detecting NMR in the nT to mT range. I am interested in the processes by which polarized nuclei return to thermal equilibrium under these conditions (i.e. relaxation rates) and the information they provide on inter-molecular and intra-molecular dynamics in liquids. At Cambridge we have built a “minimalist” OPM operating via nonlinear magneto-optical rotation (NMOR) in spin-exchange-relaxation-free (SERF) rubidium 87 and open-source tools including the popular Arduino family of microcontrollers. This setup is used to detect NMR signals from small quantities of liquid (~50 uL) imbibed into porous catalyst support materials. By measuring the relaxation due to transient adsorption at the surface sites, in low magnetic field, we seek to improve understanding of how molecules behave in confined spaces and at surfaces.

Posters

Posters will be presented in the Scott Room upstairs on the first floor of the building. Poster boards are A0, portrait orientation.

An on-scalp MEG system based on optically-pumped magnetometers

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Magnetoencephalography (MEG) is a non-invasive functional neuroimaging method for investigating electric neuronal activity of the living human brain. The magnetic field produced by neural currents is measured using sensors positioned around the head. Here we describe an *on-scalp* MEG system using optically-pumped magnetometers (OPMs).

Recently developed OPMs have high enough sensitivity to be applied for MEG, and do not require the same degree of thermal insulation as low-T_c SQUIDs. Thus, OPMs can be placed almost directly on the scalp, considerably boosting both the sensitivity to neural sources as well as spatial resolution in comparison to conventional SQUID-based MEG in which the sensors are 2–3 cm away from scalp [1,2]. For practical OPM-MEG measurements, we apply OPMs (QuSpin Inc., Louisville, CO, USA) in a rigid sensor helmet with identical geometry to that of the MEGIN (MEGIN Oy, Helsinki, Finland) SQUID-based MEG system. Individual OPMs are placed into sockets, whose positions and orientations correspond to those of the MEGIN system, and inserted until touching the head of the subject. For data acquisition, we use a modified MEGIN data acquisition system, which enables convenient usage in a well established workflow, including online averaging and data analysis (e.g. for brain–computer interfaces).

To enable source estimation, one needs to co-register the MEG data to MRI. Accurate co-registration is particularly important in on-scalp MEG [3] due to its high spatial resolution. In our OPM-MEG system, we apply a structured-light scanner to digitize the subject head surface together with the sensor helmet. This digitized surface is then aligned to the head surface derived from the subject's MR image, as well to the known geometry of the sensor helmet.

Our OPMs – operating in the spin exchange relaxation-free (SERF) regime – require the absolute magnetic field to be small in order to achieve high sensitivity. We apply a set of large coils to actively control the magnetic field up to the first-order gradients over a volume to address the following issues. First, the coil system can null the static field within this head-sized volume to minimize field changes experienced by OPMs due to their movement with respect to the remanent field (e.g., movement of the subject's head with OPMs attached). Second, it can dynamically compensate the field based on OPM outputs to remove slow field changes due to head movement and temporal drifts of the field. We highlight the importance of operating OPMs under negative feedback to ensure sufficient calibration accuracy for MEG. We implemented negative feedback using a large coil set; however, also applying feedback internally in each sensor would provide even better calibration accuracy.

We have successfully recorded both evoked and induced brain responses to visual, auditory and somatosensory stimulation with this set-up.

References

[1] E. Boto, R. Bowtell, P. Krüger, T. M. Fromhold, P. G. Morris, S. S. Meyer, G. R. Barnes, and M. J. Brookes, "On the Potential of a New Generation of Magnetometers for MEG: A Beamformer Simulation Study," PLoS One, vol. 11, no. 8, p. e0157655, Aug. 2016.

[2] J. Iivanainen, M. Stenroos, and L. Parkkonen, "Measuring MEG closer to the brain: Performance of on-scalp sensor arrays," NeuroImage, vol. 147, no. December 2016, pp. 542–553, Feb. 2017.

[3] R. Zetter, J. Iivanainen, M. Stenroos, and L. Parkkonen, "Requirements for Coregistration Accuracy in On-Scalp MEG," Brain Topogr., Jun. 2018.

Balanced planar coils for magnetic field compensation in wearable MEG

Niall Holmes, University of Nottingham

Construction of an OPM-based MEG system

Dr. James Leggett, University of Nottingham

Unshielded Atomic Magnetometry; Building a Portable, Compact Device

Carolyn O'Dwyer, University of Strathclyde

Atomic magnetometry can be used to measure magnetic fields with unshielded sensitivities in the tens of femtoTesla. [REF] In order to move from well established lab-based experiments to field-ready instruments we are developing an unshielded, portable Mx magnetometer for use in a range of environments. The double resonance technique presented here uses a single laser beam to pump thermal caesium vapour as well as phase sensitively probe its coherent precession in the presence of an RF field [2]. We aim to minimise hardware while prioritising sub-picoTesla sensitivities. Here we describe techniques to maximise sensitivity, including active noise cancellation and vapour cell optimization.

Application of SERF magnetometry to Nuclear Threat Reduction.

Abigail Langley, Robert Ward, Maxim Joseph, Joseph Watson

The Nuclear Threat Reduction programme at AWE is tasked with enhancing the detection of radiological and threat objects to strengthen border security. A particular challenge is the imaging of objects within sealed enclosures. This is crucial in the scanning of bags at airports, or fast parcel scanning in freight or as part of the postal service. These particular issues are traditionally met with X-ray radiography techniques, however, magnetic imaging is considered as a non-ionising complimentary method.
This work introduces the utilisation of a QuSpin Zero-Field atomic magnetometer in low frequency Eddy Current Induction (ECI) for the detection of conductive objects in shielded configurations. The presence of a copper disc (5mm diameter, 3mm thick) was detected behind aluminium barriers with a combined thickness of 17mm. This was achieved at frequencies <150Hz. The presence of the disc was also examined behind lead shielding (45mm thick). This has eventual applications in the detection of low conductivity metals such as uranium/plutonium in configurations which shield against conventional signatures. In addition to ECI, the QuSpin sensor was also used to observe a DC current (3mA) in a wire shielded behind aluminium. This has potential applications within electrical safety.

PicoTesla absolute field readings with a hybrid ^{3}He/^{87}Rb magnetometer

Christopher Abel, University of Sussex

Geophysical signals in the ELF band: 0.1-50 Hz

Ciaran Beggan, BGS Edinburgh

The British Geological Survey have been operating a high-frequency induction coil magnetometer (100 Hz cadence) at their observatory in Eskdalemuir (Scottish Borders) since Jun 2012. It has an approximate sensitivity of 0.07pT at 0.1-50 Hz. The geophysical signals within the dataset encompass the Schumann Resonances (SR) generated by energy from equatorial lightning refracting in the Earth-ionosphere cavity, the Ionospheric Alfven Resonances (IAR) of the upper ionosphere cavity and magnetospheric pulsations triggered by geomagnetic storms. We can also observe several subharmonics of the UK 50 Hz power grid. On occasion, local lightning strikes can also be observed directly in the data.

These signals range in amplitude from 0.5 pT for the IAR to 5 pT for the SR and up to 5 nT for proximal lightning storms. In this poster, we give examples of spectrograms showing each type of geophysical signal and describe their occurence statistics and typical amplitude ranges.

Recording the Heart Beat of Cattle using a Differential System of Optically Pumped Magnetometers

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Livestock farming occupies about 30% of the Earth's habitable surface area with a global value around £1 trillion. This important economic entity relies to a large extent on the health and welfare of the animals involved. Besides economic pressure there is also a growing interest from the consumer in the ethical keeping of livestock [Grandin 2014]. The animal's heart rate is a key indicator of stress and therefore an automated non- contact means of measuring heart beat could enable improved monitoring of animal welfare.
The electric signal of the heart muscle excitation and relaxation does also carries a magnetic field component. Reading the magnetic field to query heart beat information avoids the need for contact electrodes. We use an array of QuSpin Total Field Magnetometers (QTFM®). Using the background noise to time-shift the signals we optimize signal to noise ratio and record the magnetic heart signal down to 1 pT Hz-1/2 in the 1–20 Hz frequency band. Using a mathematical algorithm we retrieve the heart rate and the shape of the magnetic heart excitation. Comparison to electro cardiograms shows good correlation.

Non-Destructive Structural Imaging of Steelwork with Atomic Magnetometers

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We demonstrate imaging and testing of the defects in metallic samples performed with ultrasensitive radio-frequency Cs atomic magnetometer in magnetically unscreened environment with active magnetic field compensation system and a measurement geometry suitable for industrial monitoring. We explore the shape and amplitude of the spatial profile of signal features that correspond to defects. By comparing numerical and experimental results on a series of benchmark aluminium plates we demonstrate a robust process for determining defect dimensions. We present detection of thinning of carbon steel plate with a sensitivity of 0.1 mm and proof of concept measurement of structural evaluation of ferromagnetic sample in the presence of concealing conductive barrier.

Brain stimulation combined with optically pumped magnetometers

Anna Kowalczyk, University of Birmingham

Attendees

Rasmus Zetter	Aalto University
Abigail Langley	Atomic Weapons Establishment
Joe Watson	Atomic Weapons Establishment
Olivier Masseglia	Bartington Instruments
Ciaran Beggan	British Geological Survey
Mark Brannan	Cambridge Consultants
Gary Kendall	CDO2
Matt Withers	CDO2
John Burke	DARPA
Peter Schlosser	Fraunhofer CAP
Rahul Mhaskar	Geometrics, Inc
Robert Boyce	Ice Robotics Ltd
Volkmar Schultze	Leibniz IPHT
Rafal Gartman	NPL
Michael S. Larsen	Northrop-Grumman
Stephen Lee	Optocap Ltd
Douglas Bremner	Optocap Ltd
Rene Gaio	Optocap Ltd
Anthony McMahon	Peacock Technology Ltd
Clive Robinson	Peacock Technology Ltd
Kamyar Mehran	QMUL
Shweta Choudhury	QuSpin, Inc
Vishal Shah	QuSpin, Inc
Liam Williams	RSK Group
Peter Schwindt	Sandia National Laboratory
Ole Kock	Teledyne e2v
Andrew Mitchell	Teledyne e2v
Thomas W. Kornack	Twinleaf, LLC
Samantha Davidson	Ultra Electronics
Cameron Deans	UCL
Ania Kowalczyk	Birmingham University
Michael Tayler	University of Cambridge
Svenja Knappe	University of Colorado
Ben Varcoe	University of Leeds & Creavo Medical Tech
Bruce Saleeb-Mousa	Nottingham University
Dominic Sims	Nottingham University
James Leggett	Nottingham University
Kasper Jensen	Nottingham University
Niall Holmes	Nottingham University
Thomas Fernholz	Nottingham University
Dominic Hunter	Strathclyde University
Aidan Arnold	Strathclyde University
Carolyn O'Dwyer	Strathclyde University
Erling Riis	Strathclyde University
Iain Chalmers	Strathclyde University
Paul Griffin	Strathclyde University
Simon Armstrong	Strathclyde University
Stuart Ingleby	Strathclyde University
Terry Dyer	Strathclyde University
Ross Johnson	Strathclyde University
Jens Sutter	Strathclyde University
Christopher Abel	University of Sussex
Mark Bason	University of Sussex
Peter Krueger	University of Sussex