

Time (CET)	MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY
12.45 - 13.45	(week before: online talks J. Marohn N. Arunkumer P. Willke)		Discussion <i>(KOR - EUR)</i> (wonder)		
13.45 - 14.00	13.40 - Opening <i>(Plenary channel)</i>		<i>Break</i> (wonder)		
14.00 - 15.00	Q&A <i>Plenary talks</i> J. Marohn N. Arunkumer P. Willke <i>Chair: Andreas Heinrich</i> <i>(Plenary channel)</i>	Podium conversation <i>Spin manipulation</i> H. Haas, T. Taminiiau, Y. Bae <i>Chair: C. Degen</i> <i>(Plenary channel)</i>	Talks 3 <i>2 parallel sessions</i> <i>(Parallel session channels)</i>	Podium conversation <i>Sensor position</i> R. Budakian, A. Finkler, A. Singha <i>Chair: P. Maurer</i> <i>(Plenary channel)</i>	Podium conversation <i>Technical aspects</i> T. Oosterkamp, V. Vorobyuv, T. Seifert <i>Chair: P. Maletinsky</i> <i>(Plenary channel)</i>
15.00 - 15.15	<i>Break</i> (wonder)	<i>Break</i> (wonder)	<i>Break</i> (wonder)	<i>Break</i> (wonder)	<i>Break</i> (wonder)
15.15 - 16.15	Talks 1 <i>2 parallel sessions</i> <i>(Parallel session channels)</i>	Talks 2 <i>2 parallel sessions</i> <i>(Parallel session channels)</i>	Podium conversation <i>Dissipative phenomena</i> A. Eichler, T. van der Sar, F. Donati <i>Chair: M. Ternes</i> <i>(Plenary channel)</i>	Talks 4 <i>2 parallel sessions</i> <i>(Parallel session channels)</i>	Discussion & Conclusion (wonder)
16.15 - 16.30	<i>Break</i> (wonder)	<i>Break</i> (wonder)	<i>Break</i> (wonder)		
16.30 - 17.00	Speed-Dating (wonder)	Discussion <i>(EUR - USA)</i> (wonder)	BINGO (wonder)		

Virtual locations:

- The different channels can be found in MS teams
- Wonder can be accessed from the “Coffee room” channel on MS teams

Talks schedule

Talks 1 - Monday

	Parallel session A	Parallel session B
15.15-15.35	Marc-Dominik Krass	Dr Michael Barson
15.35-15.55	Alex Healey	Gernot Gruber
15.55-16.15	Tim Fuchs	Matthew Cambria
Chair	Christopher Klug	Inbar Zohar

Talks 2 - Tuesday

	Parallel session A	Parallel session B
15.15-15.35	Guanzhong Wu	Dr Ravid Shaniv
15.35-15.55	Guoqing Wang	Peter Sun
15.55-16.15	Michael Boucher	Ishita Kemeny
Chair	Vadim Vorobev	Samer Kurdi

Talks 3 – Wednesday

	Parallel session A	Parallel session B
14.00-14.20	Yi Chen	Raphael Pachlatko
14.20-14.40	Maxime Rollo	Robbie Elbertse
14.40-15.00	Stepan Kovarik	Patrick Reiser
Chair	Richard Schlitz	Dominik Bucher

Talks 4 - Thursday

	Parallel session A	Parallel session B
15.15-15.35	Iacopo Bertelli	Letizia Catalini
15.35-15.55	Kristina Liu	Simon Brecht
15.55-16.15	David Hälg	David Collomb
Chair	Nazanin Mosavian	Gesa Welker

Plenary talk abstracts:

A Magnetic Resonance Force Microscopy Tutorial

John A. Marohn, Cornell University

In this tutorial talk I will cover the principles of magnetic resonance force microscopy, MRFM, and summarize the state-of-the-art. I will cover the basics of magnetic resonance, explain how to detect spins as a force or a force-gradient acting on a microcantilever, and state sample requirements and restrictions. I will discuss detecting both electron spins and nuclear spins. We will need to discuss spin noise and what makes detecting spin fluctuations especially challenging. I will discuss MRFM sensitivity, highlight milestone results, and survey ongoing work to improve sensitivity, improve resolution, and apply MRFM to interesting science puzzles.

I have been in the business of ultrasensitive magnetic resonance for a long time and will bring my big-picture perspective to the tutorial and subsequent discussions. While still a graduate student, I attended the first public talk by John Sidles proposing MRFM to the Experimental Nuclear Magnetic Resonance Conference. Since then, the MRFM community has improved sensitivity by approximately 12 orders of magnitude. Before MRFM, I developed MRI techniques for imaging solids and carried out optically detected magnetic resonance experiments on semiconductors. As an Assistant Professor I took up electric force microscopy, using it to study charge motion in organic and hybrid semiconductors and understand charge fluctuations and the origins of non-contact friction. On my last sabbatic, I learned biology and cryo-electron microscopy at The Scripps Research Institute. This background gives me a unique perspective on the need for MRFM and the challenges we are likely to face in applying MRFM to study materials and biological structures.

Introduction to NV's - Micron-scale NMR Spectroscopy using Quantum Defects in Diamond

Nythia Arunkumar, North Carolina State University

Optically-probed nitrogen-vacancy (NV) quantum defects in a diamond can detect nuclear magnetic resonance (NMR) signals with high-spectral resolution from micron-scale sample volumes of about 10 picoliters [1, 2]. I will introduce the basics of NV sensing and explain the limits of sensing sensitivity and resolution as demonstrated in recent experiments aimed at these limits. A key challenge for NV-NMR is detecting samples at millimolar concentrations. In this talk, I will discuss our recent experiments where we demonstrate an improvement in NV-NMR proton concentration sensitivity of about 10^5 over thermal polarization by hyperpolarizing sample proton spins through signal amplification by reversible exchange (SABRE). Thus, enabling micron-scale NMR of small molecule sample concentrations as low as 1 millimolar in picoliter volumes [3]. The SABRE-enhanced NV-NMR technique may facilitate detection and chemical analysis of low concentration molecules and their dynamics in complex micron-scale systems such as single-cells.

[1] Glenn et al., Nature 555, 351 (2018).

[2] Bucher et al., Phys. Rev. X 10, 021053 (2020).

[3] Arunkumar et al., PRX Quantum 2, 010305 (2021).

Magnetic Sensing of Single Atomic and Molecular Spins on Surfaces

Philip Willke, Physikalisches Institut, Karlsruhe Institute of Technology

In this talk, I will introduce the recently realized combination of electron spin resonance and scanning tunneling microscopy [1] (ESR-STM) as a new architecture for nanoscale magnetic sensing. It allows to address single atoms and molecules on surfaces with unprecedented energy resolution. This novel technique can be used to sense the magnetic coupling between atomic spin centers when they are just a few nanometers apart [2], along with their dynamics [3,4]. When scanning the STM tip across the surface it permits to perform magnetic resonance imaging on the atomic scale [5]. The high energy resolution also grants access to the hyperfine interaction between the electron and nuclear spin of different atomic species [6]. Moreover, we could extend this technique recently to spin resonance on individual molecules [7]. Lastly, by employing pulsed ESR schemes a coherent manipulation of the surface spin becomes possible, for instance in Rabi and Hahn echo schemes [8]. This opens up a path towards quantum information processing and quantum sensing using atomic building blocks, including atoms and molecules.

1. S. Baumann, W. Paul et al., *Science* 350, 6259 (2015).
2. T. Choi, ..., PW, et al. *Nature Nanotechnology* 12, 420-424 (2017).
3. F. Natterer, ..., PW, et al., *Nature* 543, 226 (2017).
4. L. Veldman, L. Farinacci et al., arXiv:2101.10765 (2021).
5. P. Willke et al., *Nature Physics* 15, 1005–1010 (2019).
6. P. Willke et al., *Science* 362, 336–339 (2018).
7. X. Zhang, ..., PW, et al., <https://www.researchsquare.com/article/rs-134144/v1>
8. K. Yang, ..., PW, et al., *Science* 366, 509-512 (2019).

Talk abstracts

Imaging a Virus: Advances in 3D Magnetic Resonance Force Microscopy

M.-D. Krass, ETH Zürich

Discussant: Francisco Ayala Rodriguez, Ohio State university

The goal of nanoscale magnetic resonance imaging (NanoMRI) is the 3D visualization of nuclear spin densities inside objects with near-atomic spatial resolution. One promising candidate for NanoMRI is magnetic resonance force microscopy (MRFM) which employs an ultrasensitive nanomechanical transducer to detect the interaction between nuclear spins and a magnetic field gradient. Recently, we achieved an important milestone on the way to establish subnanometer-resolution MRFM by demonstrating line scans with a 1D resolution of 0.9 nanometer [1]. We also present first data from our latest 3D scan of single influenza virus particles. Current efforts involve new image reconstruction methods that account for strong static and dynamic cantilever-surface interactions.

[1] U. Grob, M. D. Krass, M. Héritier, R. Pachlatko, J. Rhensius, J. Košata, B. A. Moores, H. Takahashi, A. Eichler, and C. L. Degen, *Nano Letters* (2019), 19, 11, 7935 – 7940

Polarization of molecular samples using nitrogen-vacancy center ensembles: results and outlook

Alex Healey, Melbourne University

Discussant: William Beatrez, Berkeley

Following a number of proof-of-principle experiments, NV centers in diamond have been proposed as a platform for improving the sensitivity of NMR experiments through hyperpolarization of nuclear spins in molecular samples. This technique has benefits over current alternatives due to its potential in achieving non-invasive, room temperature hyperpolarization, however faces a number of challenges before its ultimate implementation. Through theoretical modelling of the polarization process [1] and an experimental extension of previous results [2], we identify and assess these challenges. We find that improvement of diamond material properties and microstructuring of the sample-substrate interface will be important in the development of this platform, which remains promising for the hyperpolarization of macroscopic and uL-scale samples.

[1] J.-P. Tetienne, L.T. Hall, A. J. Healey, G. A. L. White, M.-A. Sani, F. Separovic, and L. C. L. Hollenberg, *Phys. Rev. B* (2021), 103, 014434

[2] A. J. Healey, L. T. Hall, G. A. L. White, T. Teraji, M.-A. Sani, F. Separovic, J.-P. Tetienne, and L. C. L. Hollenberg, *Phys. Rev. App.* (2021), 15, 054052

Towards Single Electron Spin MRFM at Millikelvin Temperatures

Tim Fuchs, Leiden University

Discussant: Jaimy Plugge, Leiden University

SQUID-detected Magnetic Resonance Force Microscopy (MRFM) has been shown to be a very sensitive magnetic force sensor at mK temperatures (400zN/rtHz, [1]). MRFM can be used to probe electron spin states. Electron spins in NV-centra have been extensively researched as Qubit-systems, and their quantum state can be readily controlled through Radio-Frequency (RF) pulses.

We have recently finished work on a new set-up, with which we hope to measure a single electron spin in a very pure platelet of diamond [2] using an IBM cantilever in a SQUID-detected MRFM system. By applying RF pulses we aim to control the state of the electron spin, with as eventual goal to couple our cantilever to the electron spin. Here our long-term goal is to use this to create a macroscopic superposition state of our cantilever.

In my talk, I will mostly focus on the experimental challenges of our research so far.

[1] M. de Wit, G. Welker, J. J. T. Wagenaar, F. G. Hoekstra, and T. H. Oosterkamp, *Journal of Applied Physics*, 125, 083901 (2019)

[2] Courtesy of M. Ruf, R. Hanson, TU Delft

Dr Michael Barson, Monash University

Discussant: Nazanin Mosavian, University of New Mexico

The nitrogen-vacancy (NV) centre in diamond has proven itself as a sensitive magnetometer with the capability to image magnetic fields with nanometre scale resolution. Less developed is its ability to also perform as a sensitive electrometer. The NV centre is unique in its ability to perform nanoscale vector electric field imaging with single electron sensitivity at room temperature and pressure. This is important as many interesting electrical processes are strongly temperature dependent, e.g. charge transport in electronics or chemical processes. I will discuss my recent work that performed nanoscale vector electric field imaging, with sensitivity sufficient to measure the electric field from a single electron. I will discuss the experimental requirements to perform NV electrometry and a useful measurement technique I discovered that dramatically improves the field amplitude dynamic range of such a measurement. I will also mention the invention of a novel high-field 3D electromagnet designed for scanning probe NV experiments that I am in the process of commercializing.

Towards MRFM using carbon nanotube cantilevers

Gernot Gruber, ICFO

Discussant: Chanhghao Li, MIT

Nanomechanical resonators are excellent force sensors for the detection of small nuclear spin ensembles on the nanoscale.[1-3] Due to their small size and mass, single wall carbon nanotubes are a class of resonators holding great potential for the force detection of individual nuclear spins. Recently, our group reported on a hybrid carbon nanotube cantilever, with an impressive force sensitivity of 767 zN/√Hz at room temperature.[4] The resonator is composed of a singly clamped nanotube grown by chemical vapour deposition. Subsequently, a platinum nanoparticle is deposited at the free end of the nanotube via an electron microscope with a gas injection system. The nanoparticle efficiently scatters light, enabling the optical detection of the thermal vibrations of the nanotube with high signal to noise ratio. We recently introduced a mass sensing method to control the amount of deposited material during growth with a mass resolution in the zeptogram range.[5] This technique relies on monitoring the resonance frequency of the resonator during the deposition process via e-beam electro-mechanical coupling. Here, we show further advancements in the fabrication of hybrid nanotube cantilevers and their application as ultra-sensitive vectorial scanning probes. We show opto-mechanically acquired 2D maps of nano-patterned Au wires and investigate broadening effects of the mechanical resonance due to interactions of the cantilever tip with the Au surface.

[1] H. J. Mamin, M. Poggio, C. L. Degen, and D. Rugar, *Nature Nanotech.* 2, 301 (2007).

[2] C. L. Degen, M. Poggio, H. J. Mamin, C. T. Rettner, and D. Rugar, *PNAS* 106, 1313 (2009).

[3] J. M. Nichol, T. R. Naibert, E. R. Hemesath, L. J. Lauhon, and R. Budakian, *Phys. Rev. X* 3, 031016 (2013).

[4] A. Tavernarakis, A. Stavrinadis, A. Nowak, I. Tsioutsios, A. Bachtold, and P. Verlot, *Nature Comm.* 9, 662 (2018).

[5] G. Gruber, C. Urgell, A. Tavernarakis, A. Stavrinadis, S. Tepsic, C. Magén, S. Sangiao, J. M. de Teresa, P. Verlot, and A. Bachtold, *Nano Lett.* 19, 6987 (2019).

Matthew Cambria, University of Wisconsin-Madison

Discussant: Ahmed Safa, KIT

Understanding the limits to the electronic spin coherence of the nitrogen-vacancy (NV) center in diamond is vital to realizing the full potential of this quantum system. In prior work, we found that at room temperature the double-quantum relaxation rate is approximately twice the single-quantum relaxation rate, limiting the maximum theoretically achievable coherence time for an NV under ambient conditions to 6.8(2) ms. We presented theoretical arguments showing that the two-phonon Raman process which is believed to provide major contributions to the single-quantum relaxation rate at 295 K is forbidden from driving double-quantum relaxation [1]. Here we present experimental measurements of the phonon-limited double-quantum relaxation rate of the NV as a function of temperature. In addition, we discuss our theoretical efforts towards understanding the observed temperature dependence of the double-

quantum relaxation rate, which may shed new light on spin-phonon coupling in the NV and may inform strategies to mitigate this relaxation.

[1] M. C. Cambria, et al., State-dependent phonon-limited spin relaxation of nitrogen-vacancy centers, *Phys. Rev. Research* 3, 013123 (2021).

Guanzhong Wu, Ohio State University

Discussant: Richard Schlitz, ETH Zürich

Spin pumping enhanced Gilbert damping in ferro- or ferrimagnetic (FM) system has been extensively studied in the past decades. However, studies on spin pumping between FM and two-dimensional (2D) materials is still challenging, due to 2D materials' reduced size. In this talk, I will present a technique that enables the imaging of Gilbert damping spatial variation caused by a spin sink with micron-scale lateral dimension overlaid on a FM thin film [1]. The key idea is to extract Gilbert damping utilizing resonance cone angle rather than resonance linewidth using ferromagnetic resonance force microscope (FMRFM). The reason is that in the FMRFM set up, compared to the resonance linewidth, which is susceptible to the cantilever oscillation disturbance, the resonance cone angle is not affected, and therefore, is inversely proportional to the Gilbert damping. Moreover, the cone angle in FMRFM is easy to measure since it is directly related to the dipolar force exerted on the tip, and therefore, the resonance peak amplitude. This technique makes it possible to simultaneously image the magnetic anisotropy and the Gilbert damping at a single RF frequency with a spatial resolution of $\sim 100\text{nm}$. It is promising to be applied to study spin pumping from YIG to various kinds of 2D materials.

[1] Wu, Guanzhong, Yang Cheng, Side Guo, Fengyuan Yang, Denis V. Pelekhov, and P. Chris Hammel. "Nanoscale imaging of Gilbert damping using signal amplitude mapping." *Applied Physics Letters* 118, no. 4 (2021): 042403.

Guoqing Wang, MIT

Discussant: Domenico Paone, Max Planck Institute

The nanoscale detection of vector AC magnetic fields is desirable in applications ranging from fundamental physics, such as detecting dynamic properties of spins and charges in quantum materials, to engineering, such as microwave (MW) device characterization and optimization. Isolated quantum spin defects, such as the nitrogen-vacancy center in diamond, can reach the desired nanoscale resolution, in addition to providing other advantages, such as high sensitivity, k-space resolution, etc. However, existing protocols for vector AC magnetometry based on NV centers rely on different orientations of an ensemble of quantum sensors, with degraded spatial resolution, and a protocol based on a single NV center is still lacking. Here, we propose and demonstrate the first protocol for vector AC magnetometry based on a single NV center, which achieves nanoscale resolution. By tuning a coherent MW drive to different resonance conditions, our protocol can robustly reconstruct the 3D components of a vector AC magnetic field with the same control sequence. We map the spatial distribution of an AC field generated by a copper wire on the surface of the diamond. The proposed protocol combines high sensitivity, broad

dynamic range, and sensitivity to both coherent and stochastic signals, with broad applications in various areas such as probing spin anisotropy in condensed matter physics. Our paper will soon appear on Nano Letters (accepted), and a preprint version is available at <https://arxiv.org/abs/2103.12044>.

Novel Sample Preparation and Force-Gradient Detection for Imaging of Nitroxide Radicals

Michael Boucher, Cornell University

Discussant: Eric Langman, Niels Bohr Institute

One possible application for Magnetic Resonance Force Microscopy (MRFM) is the mechanical detection and imaging of electron spins [1,2]. In 2004, Rugar et al. demonstrated single electron imaging, albeit with a specialized sample and 13-hour per data point averaging time [3]. Our protocol broadens the applicability of MRFM to fast-relaxing electron spins used in biological spin labeling by observing spins through a microwave-induced change in the force gradient, observed as a modulated shift in the cantilever frequency [1,2]. Electron spin frequency-shift experiments have shown reasonable agreement between observed and calculated signals when carried out with micron-scale nickel tips [1]. In experiments with ~100 nm diameter nickel [4] and cobalt [5] tips, in contrast, this agreement has been poor. One of the challenges of frequency-shift detection is that noise is minimized by driving the cantilever to large amplitudes. We show that large-amplitude tip motion leads to two complications. First, applying long microwave pulses to achieve maximal spin saturation blurs the point-spread function when the cantilever amplitude is large. Second, with small tips (i.e., large gradients), large amplitude motion leads to reduced signal because sample spins do not spend enough time in the resonant slice to fully saturate. We analytically and numerically calculate these effects of tip motion on sample saturation and introduce ways to improve saturation on a limited microwave power budget while maintaining a large drive amplitude. We will present recent experimental data including a new sample preparation technique that reduces frequency noise from sample dielectric fluctuations by applying a metallic coating while avoiding exposing fragile radical spins to metal deposition. We will discuss other possible sources of signal loss in small-tip experiments, including thermomagnetic fluctuations from the sample coating.

[1] E. W. Moore, S. Lee, S. A. Hickman, S. J. Wright, L. E. Harrell, P. P. Borbat, J. H. Freed, and J. A. Marohn, PNAS 106, 22251 (2009). <http://dx.doi.org/10.1073/pnas.0908120106>.

[2] H. L. Nguyen and J. A. Marohn, arxiv 1802.07247v1. <http://arxiv.org/abs/1802.07247>

[3] D. Rugar, R. Budakian, H. J. Mamin, and B. W. Chui, Nature 430, 329 (2004). <http://dx.doi.org/10.1038/nature02658>

[4] S. A. Hickman, E. W. Moore, S.-G. Lee, J. Longenecker, S. J. Wright, L. E. Harrell, and J. A. Marohn, ACS Nano, 4(12), 7141 (2010). <https://doi.org/10.1021/nn101577t>.

[5] C. Isaac, Ph.D. Thesis, Cornell University (2018).

Dr Ravid Shaniv, JILA, University of Colorado

Discussant: Jaimy Plugge, Leiden University

Mechanical detection of nuclear spin resonance has been a fruitful research avenue for a few decades. The typical mechanical spin detection setup includes a sample of spins, mechanical resonator with a magnetic tip attached to it, an interferometer designated to measure the resonator amplitude or frequency and an oscillating magnetic field source for spin manipulation. To the best of our knowledge, all past and current mechanical spin detection experiments aim to detect the longitudinal magnetization: the spins are driven by an external oscillating magnetic field, and the mechanical resonance is tuned to match the driven precession frequency proportional to it, and not the “bare” Larmor frequency. In our experiment, we plan to explore the possibility of mechanical nuclear spin detection at the Larmor frequency, by employing high-frequency mechanical resonance using a tensioned silicon-nitride membrane and detect the transverse magnetization. As a first proof-of-principle demonstration, we aim to detect the free-magnetization-decay force from large ensemble of ^{19}F nuclear spins from powder calcium fluoride, without the application of oscillating magnetic fields. Our plan incorporates techniques like pre-magnetization, working in low field and low temperature regime and fast field switching. In this talk, I will present our experimental plan, work-in-progress setup and some challenges this experiment entails.

A Python Package for Calculating MRFM Signals

Peter Sun, Cornell University

Discussant: Nils Prumbaum, ETH Zürich

Magnetic resonance force microscope (MRFM) experiments pushing sensitivity and resolution have an inherently low signal-to-noise ratio, requiring long signal-averaging times. Before performing such experiments, it is important to calculate the signal first. These calculations become crucial for making experimental decisions involving tip diameter, tip-sample separation, frequency- or field-sweep range, irradiation power and duration, and signal averaging time. Moreover, the signal calculation is a crucial first step in image reconstruction in MRFM imaging experiments. There is now a wide range of electron- and nuclear-spin MRFM experiments being performed. Some experiments detect Curie-law magnetization while others detect spin fluctuations; spin magnetization is modulated using saturation, pulses, or adiabatic inversion; and spin signals are observed using either force or force gradients, with the cantilever either stationary or moving. This diversity of experiments calls for a fast, flexible and reliable signal simulation platform, ideally open-source and experimentally validated against a wide range of experiments. We introduce a Python simulation package, *mrfmsim*, describe its capabilities and limitations, and illustrate how it can be used to simulate a wide array of MRFM experiments. Not all published MRFM signals have been compared to a signal simulation; we will show examples where the agreement between published signal and calculated signal is in some cases reasonably good and in other cases quite poor. We discuss challenges we have encountered in coding a flexible and fast simulation package, evaluating and improving simulation performance, and simulating both MRFM signals and MRFM imaging experiments.

Ishita Kemeny, University of Wisconsin- Madison

Discussant: Florentin Fabre, Laboratoire Charles Coulomb, Montpellier

Nitrogen vacancy (NV) centers in diamond have diverse applications in quantum technologies which require a good control over their charge state. While optical excitation is often used to manipulate and detect the NV center's charge states, capture of free electrons and holes from the surrounding can also change their charge states. However, little is known about charge transport dynamics in diamond, especially between individual defects. We introduce a novel technique to probe charge carrier diffusion in diamond using single-shot charge state readout of an isolated NV center. By mapping the change in charge state of the NV center to the spatial position of optical illumination, we study the charge transport and capture process of surrounding defects. Using this technique, we identify the optically dark state of silicon vacancy (SiV) centers, when illuminated with visible laser frequency, is $S_{iV}2^-$.

Yi Chen, Center for Quantum Nanoscience

Discussant: Piotr Kot, Max Planck Institute

STM-ESR has so far been limited to the driving of a single spin under the tip. In this talk I'll present techniques that allow us to drive a remote spin not directly under the tip. To demonstrate the remote spin driving, I'll present measurement results based on electron-electron double resonance spectroscopy. The ability to drive multiple spins with STM opens the door to coherent control of tailored quantum nanodevices on a surface.

Quantitative study of the response of a single NV defect in diamond to magnetic noise

Maxime Rollo, Laboratoire Charles Coulomb, Montpellier

Discussant: Paul Lehman, Uni Basel

The dynamical study of the nitrogen-vacancy (NV) defect is a powerful tool to image randomly fluctuating magnetic signals. The longitudinal spin relaxation of the NV center is indeed accelerated in the presence of magnetic noise featuring a spectral component at its spin resonance frequency. Instead of recording this relaxation time to probe the magnetic noise, we here propose a novel strategy which relies simply on the measurement of the NV center photoluminescence (PL) level. By applying a calibrated and tunable magnetic noise on a single NV defect, we show that the reduction of the relaxation time, also comes with a reduction of the PL level, which we explain by use of a simplified three level model of the defect [1]. This PL variation with the magnetic noise at the spin resonance frequency offers a simple, all-optical method to detect the magnetic noise at the nanoscale [2].

[1] M. Rollo et al. arXiv:2101.00860 (2021)

[2] A. Finco et al. Nat. Commun.12 (2021), 767

Longitudinal and transverse electron paramagnetic resonance in a scanning tunneling microscope

Stepan Kovarik, ETH Zürich

Discussant: Taehong Ahn, Center for Quantum Nanoscience

Combining electron paramagnetic resonance (EPR) with scanning tunneling microscopy (STM) enables detailed insight into the interactions and magnetic properties of single atoms on surfaces [1]. However, for the application of this novel technique as an analytical tool, the mechanisms underlying the excitation and detection of EPR need to be established. To characterize them, we deposited Fe and TiH atoms on two monolayers of MgO grown on Ag and then excited the respective EPR with a radio frequency antenna coupled to the STM tip [2]. The highly efficient implementation of EPR into the STM enabled systematic studies of the tunneling parameters and excitation amplitudes on the single-atom EPR over a broad range of values. We interpreted the data based on density functional theory and charge transfer multiplet calculations to identify the distinct components of the tip magnetic field driving the EPR transition of Fe and TiH in STM [3].

[1] S. Baumann, W. Paul, T. Choi, et al., *Science* 350, 417 (2015).

[2] T. S. Seifert, S. Kovarik, C. Nistor, et al., *Phys. Rev. Research* 2, 013032 (2020).

[3] T. S. Seifert, S. Kovarik, D. M. Juraschek, et al., *Sci. Adv.* 6, eabc5511 (2020).

Raphael Pachlatko, ETH Zürich

Discussant: Christopher Klug, Naval Research Laboratory, Washington

Magnetic Resonance Force Microscopy (MRFM) combines Nuclear Magnetic Resonance with Atomic Force Microscopy and Microwave Electronics to image single spin-active samples. System stability is paramount for MRFM measurements due to long integration times; physical cantilever pinning and resonance frequency shifts play a significant role in it. By adopting a planar geometry for the magnetic field gradient source inside the microstrip (Embedded Nanomagnets) we aim to eliminate cantilever pinning phenomena and resonance frequency spikes. The fabrication of the Embedded Nanomagnets makes heavy use of both Glancing Angle and Steep Angle Ion Milling.

Robbie Elbertse, TU Delft

Discussant: Jiyeon Hwang, Center for Quantum Nanoscience

In recent years Electron Spin Resonance (ESR) incorporated into Scanning Tunnelling Microscopy (STM) has shown tremendous results [1]. These include coherent manipulation of quantum spins and sub- μeV energy resolution. This technique relies on passing a Radio Frequency (RF, order GHz) signal down to the tunnelling junction. One of the main limitations to this is significant losses of signal along the cabling. As shown by Seifert et al. [2] it is possible to install an antenna close to the STM tip with specialized RF-cabling for increased output. Here we show a similar solution, based on commercially available products, where we also show the transmission function of the various parts of the setup. The effects of tip length

are shown, whereby a smaller tip is suitable for smooth transmission functions, and longer tips are optimal for increased output at certain frequencies.

[1] S. Baumann et al. Electron paramagnetic resonance of individual atoms on a surface. *Science* 350 417-420 (2015)

[2] T.S. Seifert et al. Single-atom electron paramagnetic resonance in a scanning tunnelling microscope driven by a radio-frequency antenna at 4K. *Phys. Rev. Res.* 2, 013032 (2020)

Quantitative scanning NV magnetometry on 2D in-plane ferromagnets at cryogenic temperatures

Patrick Reiser, Uni Basel

Discussant: David Collomb, KIT

The discovery of ferromagnetic 2D van-der-Waals system enables the study of exotic magnetic phenomena at a reduced dimensionality. One such material is CrCl₃, which exhibits an in-plane magnetization with a weak magnetic anisotropy, making it an ideal candidate for dynamically controlling the magnetization direction. However, the expected low critical temperature of the monolayer and its in-plane orientation of the magnetic state requires a non-invasive measurement scheme with a high sensitivity and spatial resolution. The scanning nitrogen-vacancy magnetometry is an ideal probe that exhibits these traits. Here I present preliminary results on measurement with these scanning probes on CrCl₃ crystals down to the monolayer. Its magnetic state is disturbed by the measurement scheme, and I discuss strategies to reduce the impact of our technique. Additionally, I provide an outlook on the 2D in-plane ferromagnet EuGe₂ grown by molecular beam epitaxy to study the geometric anisotropies in such a system.

Iacopo Bertelli, TU Delft

Discussant: Johannes Cremer, Harvard

Spin waves in magnetic insulators are low-dissipation excitations that can be used to coherently transmit and process information in future spintronic devices. The excitation, control and detection of spin waves usually involve the use of metallic electrodes. It is therefore important to study the metal-induced damping of propagating spin-waves. However, characterizing this process requires direct access to the magnetic film buried under metallic layers, which are opaque to optical probes. Here we show that, because the spin-wave stray field can penetrate metals, ensembles of NV centers in diamond enable the detection of spin waves propagating underneath metallic films. We theoretically derive an effective damping parameter that matches well with the detected damping increase by 2 orders of magnitude. Additionally, we reveal scattering centers buried under metallic electrodes, highlighting the power of our technique to assess the quality of spintronics devices and heterostructures. Our results pave the way to study interfacial metal – spin-wave interactions and processes such as spin-wave injection by the spin-Hall effect.

Surface NMR using quantum sensors in diamond

Kristina Liu, TU Munich

Discussant: Emma Huckestein, University of Maryland

Characterization of the molecular properties of surfaces under ambient or chemically reactive conditions is a fundamental scientific challenge. Nuclear magnetic resonance (NMR) spectroscopy would be the ideal technique, however it lacks the sensitivity to probe the small number of spins at interfaces. Here we use nitrogen vacancy (NV) centers in diamond as quantum sensors to optically detect NMR signals from chemically modified thin films. Aluminum oxide (Al₂O₃) layers, common supports in catalysis and materials science, are prepared by atomic layer deposition and are subsequently functionalized by phosphonate chemistry to form self-assembled monolayers (SAMs). The surface NV-NMR technique detects NMR signals from the monolayer, indicates chemical binding, and quantifies molecular coverage. In addition, it can monitor in real-time the formation kinetics at the solid-liquid interface. This work demonstrates the capability of NV quantum sensors as a surface-sensitive (femtomole) NMR tool for in-situ analysis in catalysis, materials and biological research.

David Hälg, ETH Zürich

Discussant: Parul Devi, Center for Quantum Nanoscience

We report the development of a scanning force microscope based on an ultra-sensitive silicon nitride membrane optomechanical transducer. Our development is made possible by inverting the standard microscope geometry - in our instrument, the substrate is vibrating and the scanning tip is at rest. We present first topography images of samples placed on the membrane surface. Our measurements demonstrate that the membrane retains an excellent force sensitivity when loaded with samples and in the presence of a scanning tip. We discuss the prospects and limitations of our instrument as a quantum-limited force sensor and imaging tool.

Modelling and observation of nonlinear damping in dissipation-diluted nanomechanical resonators

Letizia Catalini, University of Copenhagen

Discussant: Ye Tao, Harvard University

In the last decades, significant progress in engineering micro- and nanomechanical resonators has resulted in a rich number of applications in sensing experiments and quantum science, where high coherence has critical role. To this end, the introduction of the dissipation dilution enables extremely low linear loss in stressed nanomechanical resonators, such as strings or membranes. In the last decades, significant progress in engineering micro- and nanomechanical resonators has resulted in a rich number of applications in sensing experiments and quantum science, where high coherence has critical role. To this end, the introduction of the dissipation dilution enables extremely low linear loss in stressed nanomechanical resonators, such as strings or membranes. The low mass of these resonators, combined with their high quality factors, makes them a promising platform for magnetic resonance force microscopy (MRFM) experiments, by enabling force sensitivity on the order of the order of $aN/\sqrt{\text{Hz}}$.

Here, we report on the observation and theoretical modelling of nonlinear dissipation in such structures. We introduce an analytical model based on von Kármán theory, which can be numerically evaluated using finite-element models for arbitrary geometries. Through this approach, we predict both nonlinear loss and (Duffing) frequency shift in ultracoherent phononic membrane resonators. A set of systematic measurements on a range of complex mode shapes, geometric parameters, and temperatures shows good agreement with the model for low-order soft-clamped modes. Our analysis also reveals quantitative connections between these nonlinearities and dissipation dilution. This is of interest for future design of novel resonator geometries and the characterization of the performance of dissipation-diluted devices, yielding otherwise inaccessible insight when diagnosing their performance in an experimental setting.

Nanoscale magnetic imaging of an out-of-equilibrium magnon gas using NV magnetometry

Brecht Simon, TU Delft

Discussant: Lee Inhee, Ohio State university

Magnetometry based on nitrogen-vacancy (NV) spins in diamond has recently emerged as a powerful tool for probing spin waves –the elementary excitations of coupled spins in magnetically ordered materials. In this talk I will describe how we use NV magnetometry to show how microwave excitation of low-wavenumber spin waves leads to a high-density and, most surprising, a unidirectional gas of incoherent magnons that we probe using an ensemble of NV sensor spins that are shallowly embedded in the tip of a diamond scanning probe. We find that the enhanced magnon density extends unidirectionally over hundreds of micrometres from the excitation stripline. Furthermore, we demonstrate how the spatial decay of the stray fields reveals the wavenumber content of both coherently excited spin waves with a well-defined wavenumber as that of the incoherent magnon gas. These results reveal that coherently driven, low-wavenumber spin waves are efficient generators of a non-equilibrium magnon gas in target directions, opening new avenues for local control when driving spin transport or magnetization dynamics.

Vortex-resolved imaging of flux pinning high temperature superconducting tapes via scanning Hall probe microscopy

David Collomb, KIT

A crucial challenge in the development of high temperature superconducting (HTS) tapes is to increase the critical current density, while still maintaining a high critical temperature. A high critical current density can be achieved by carefully engineering the pinning force for superconducting vortices. This can be attained by employing a variety of different pinning strategies to maximise the critical current density including, but not limited to, normal second-phase inclusions, irradiation, nanoscale defects, surface deformation and surface decoration. In this talk I will share recent studies using quantitative magnetic imaging via scanning Hall probe microscopy on an up-to-the-minute GdBaCuO second generation HTS tape fabricated by SuNAM hosting Gd₂O₃ second phases [1]. Our low field (<1mT) magnetic images initially reveal a relatively low density of very strong pinning sites giving rise to repeatable but highly disordered vortex patterns. But most surprisingly, the peak fields and full-width-half-maxima (FWHM) of

the vortices differ dramatically from what is typically observed in 'cleaner' superconductors. The profiles of the vortices are found to be strikingly broad, several times larger than the film thickness, and barely deviate as a function of temperature from 10K to 85K. We tentatively suggest this is due to the distortion of the supercurrent by the highly dense array of normal pinning sites which ultimately results in the extension of the range of the supercurrent magnetic fields. Additionally, we correlate magnetic imaging with topographic gating and SEM images, we find that CuO_z precipitates and outgrowths, which are $\sim 1\mu\text{m}$ in size, do not represent effective pinning sites. This points towards nanoscale Gd_2O_3 second phases being the dominant pinning sites under our measurement conditions. Finally, we also perform 'local' magnetisation measurements which reveal a noticeable deviation from the accepted 2D Bean critical state model, and irreversible M-H loops have shapes closer to those predicted by a 3D critical state model. This suggests that the critical state profiles are relaxing quite rapidly due to flux creep. Although just a very simple and 'first-look' into the vortex pinning in HTS tapes, I hope that our studies can inspire a deeper delve into the pinning mechanisms, eventually helping guide materials scientists and engineers to the next frontier of HTS tapes.

[1] D. Collomb, M. Zhang, W. Yuan and S. J. Bending, "Imaging of String Nanoscale Vortex Pinning in GdBaCuO High-Temperature Superconducting Tapes", *Nanomaterials* 11(5), 1082 (2021).

E-mail: David.collomb@kit.edu