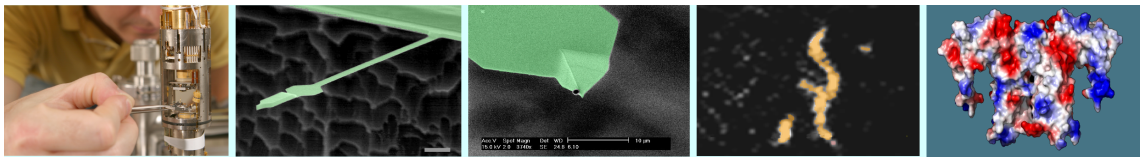


3^{rd} nano-MRI research conference

Tremblay, 12-16 July 2010

"Exploring the Frontiers of Magnetic Resonance Imaging"

12-16 July 2010, Domaine du Tremblay
78490 Le Tremblay sur Mauldre, France

Scientific commitee :

Olivier Klein (SPEC, CEA-Saclay)

Tjerk Oosterkamp (Leiden University)

John Marohn (Cornell University)

Beat Meier (ETH Zürich)

Jean-François Roch (LPQM, ENS Cachan)

Dan Rugar (IBM Almaden)

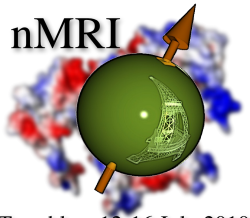
Jörg Wrachtrup (University of Stuttgart)

3rd nano-MRI research conference

http://iramis.cea.fr/meetings/nMRI

Exploring the Frontiers of Magnetic Resonance Imaging - July 12th to 16th, 2010

	Mon. July 12th	Tues. July 13th	Wedn. July 14th	Thurs. July 15th	Fri. July 16th
Breakfast	**ENS Cachan**	**Tremblay**	**Tremblay**	**Tremblay**	**Tremblay**
Introduction	*C. Colliex - RTRA 9:15am-9:30am*	*S. Rousset - CNANO 9:00am-9:15am*			
Morning 1	*M. Goldman MRI 9:30am-10:45am*	*Rugar & Meier 9:15am-10:45am*	*Balasurbramanian & Suter 9am-10:30am*	*Hammel & de Loubens 9am-10:30am*	*Sidles & Garrido 9am-10:30am*
Coffee Break	*Coffee Break*	*Coffee Break*	*Coffee Break*	*Coffee Break*	*Coffee Break*
Morning 2	*V. Jacques N-V 11:00am-12:15pm*	*Walsworth & Arnault 11:00am-12:30pm*	*Budakian & Oosterkamp 11:00am-12:30pm*	*Budker 11:00am-11:45am* *Cappellaro & Terres Hall 11:45am-12:30pm*	*Marohn, Poggio, Fermon, & Huant 11am-12:30pm*
Lunch	*ENS Cachan 12:15pm-1:30pm*	*Tremblay 12:30pm-2pm*	*Tremblay 12:30pm-2pm*	*Tremblay 12:30pm-2pm*	*Tremblay 12:30pm-2pm*
Afternoon 1	*A. Thiaville NanoMag 1:30pm-2:45pm*	*Visit of Neurospin (CEA Saclay)*	*Free*	*Shuttle to Château de Versailles*	*Shuttle back to Paris 2:00pm*
	Y. de Wilde Near Field 2:45pm-4:00pm			*Visit of Jardins du Château de Versailles*	
Afternoon 2	*Coffee Break*				
	J. Marohn MRFM 4:15pm-5:30pm				
Dinner	*Shuttle to Tremblay 5:30pm*	*Tremblay 6:30pm-7:30pm*	*Tremblay 6:30pm-7:30pm*	*Picnic in Jardins du Château de Versailles* ***(hope for no rain)***	
Evening 1	*Registration and reception in Tremblay 7pm-10pm*	*Mamin, McMichael, Treussart & Meijer 7:30pm-9pm*	*De Lange, Childress, Weiger & Sakellariou 7:30pm-9pm*		
Evening 2		*Posters 1 9pm-10:30pm*	*Posters 2 9pm-10:30pm*	*Shuttle back to Tremblay*	



Tremblay, 12-16 July 2010

Tutorials: 60'+15'
Invited talks: 30'+15'
Short talks: 15'+7'

Monday July 12th - ENS Cachan

9 :15–9 :30 **Christian Colliex** (RTRA)
Welcome–Introduction

9 :30– 10 :45 Chairman - J.-F. Roch
Maurice Goldman (CEA et Académie des sciences)
Magnetic resonance imaging

10 :45–11 :00 *Coffee break*

11 :00–12 :15 Chairman - J.-F. Roch
Vincent Jacques (LPQM - ENS Cachan)
Magnetic resonance with defects in diamond

12 :15–13 :30 *Lunch at ENS Cachan*

13 :30–14 :45 Chairman - O. Klein
André Thiaville (Laboratoire de physique des solides)
Nanomagnetism

14 :45–16 :00 Chairman - O. Klein
Yannick De Wilde (Institut Langevin, ESPCI)
Near field microscopy techniques

16 :00–16 :15 *Coffee break*

16 :15–17 :30 Chairman - O. Klein
textbfJohn Marohn (Cornell University)
Magnetic resonance force microscopy

17 :30 *Shuttle to Tremblay*

19 :00–22 :00 *Registration and reception in Tremblay*

Tuesday July 13th - Tremblay

9 :00–9 :15 **Sylvie Rousset** (C'nano IdF)
Introduction

9 :15–10 :45 Chairman - C. Hammel
Dan Rugar (IBM - Almaden)
Nanoscale magnetic resonance force microscopy : Successes, Challenges and Opportunities
-
Beat H. Meier (ETH Zürich)
-

10 :45–11 :00 *Coffee break*

11 :00–12 :30 Chairman - J. Wrachtrup
Ronald Walsworth (Harvard-Smithsonian)
NV-Diamond Magnetometry
-
Jean-Charles Arnault (CEA/DRT/LIST/DCSI)
CVD Diamond : synthesis, properties and applications

12 :30–14 :00 *Lunch at Tremblay*

14 :00–18 :30 *Visit of Neurospin (CEA Saclay)*
-
Free Time

18 :30–19 :30 *Dinner at Tremblay*

19 :30–21 :00 Chairman - K. Karrai

John Mamin (IBM - Almaden)
Exploring Methods to Overcome Force Noise in MRFM

-

Robert D. McMichael (NIST, Gaithersburg)
Interactions, fields and dynamics in ferromagnets

-

François Treussart (LPQM - ENS Cachan)
Photoluminescent diamond nanoparticles for cellular imaging and traceable drug-delivery into cell

-

Jan Maijer (RUBION, Ruhr-Universität Bochum)
Addressing and creation of single NV in diamond using ion implantation

21 :00–22 :30 ***Poster Session 1***

Wednesday July 14th - Tremblay

9 :00–10 :30 Chairman - R. Hanson
Gopalakrishnan Balasubramanian (Universität Stuttgart)
Single Defects in Diamond - Towards Sensing and Imaging Single Molecules
-
Dieter Suter (Dortmund University)
—-

10 :30–11 :00 *Coffee break*

11 :00–12 :30 Chairman - C. Degen
Raffi Budakian (University of Illinois)
Mechanical detection of magnetic resonance using nanowire cantilevers : opportunities and challenges
-
Tjerk Oosterkamp (Leiden University)
Detecting an MRFM force sensor using SQUID read-out

12 :30–14 :00 *Lunch at Tremblay*

14 :00–18 :30 *Free Time*

18 :30–19 :30 *Dinner at Tremblay*

19 :30–21 :00 Chairman - C. Fermon
Gijs de Lange (Delft University of Technology)
Universal dynamical decoupling of single electron spins in diamond
-
Lilian Childress (Bates College)
Control of individual nuclear spins in diamond
-
Markus Weiger (Bruker BioSpin)
Molecular diffusion in micro-MRI : friend or foe ?
-
Dimitrios Sakellariou (CEA/DSM/IRAMIS/SPEC)
Rotating microcoils for magnetic resonance spectroscopy and microscopy

21 :00–22 :30 ***Poster Session 2***

Thursday July 15th - Tremblay

9 :00–10 :30 Chairman - R. McMichael
Chris Hammel (The Ohio State University)
Nanoscale scanned probe ferromagnetic resonance imaging using localized modes
-
Grégoire de Loubens (CEA/DSM/IRAMIS/SPEC)
Identification and selection rules of the spin-wave eigenmodes in spin-valve nano-pillar

10 :30–11 :00 *Coffee break*

11 :00–12 :30 Chairman - P. Bertet
Dmitry Budker (University of California, Berkeley)
Diamond magnetometry for low-field NMR at the micro- and nano-meter scale
-
Paola Cappellaro (Massachusetts Institute of Technology)
Nanoscale diamond magnetometer with quantum-limited sensitivity
-
Liam Terres Hall (University of Melbourne)
NV nanodiamond decoherence detection of spins in solution

12 :30–14 :00 *Lunch at Tremblay*

14 :00–18 :30 *Shuttle to* Château de Versailles
-
Visit of Jardins du Château de Versailles

18 :30–21 :00 *Picnic in* Jardins du Château de Versailles ***(hope for no rain)***

21 :00 *Shuttle back to Tremblay*

Friday July 16th - Tremblay

9 :15–10 :45 Chairman - F. Jelezko
John Sidles (School of Medicine University of Washington Seattle)
Concentrative Dynamics Within Forms-and-Flow frameworks for Classical and Quantum Spin Simulations
-
Jose Garrido (Technische Universität München)
Diamond surfaces : functional hosts for NV centers

10 :30–11 :00 *Coffee break*

11 :00–12 :30 Chairman - O. Arcizet
John A. Marohn (Cornell University)
Force-gradient detection of electron spin resonance from a nitroxide spin label : A path to applications
-
Martino Poggio (Universität Basel)
Towards nano-MRI and in mesoscopic transport systems
-
Claude Fermon (DSM/IRAMIS/SPEC-CEA Saclay)
Magnetoresistive hybrid sensors for very low-field MRI
-
Serge Huant (Institut Néel)
Near-field scanning single-photon microscopy with an individual NV-center : some possible applications

12 :30–14 :00 *Lunch at Tremblay*

14 :00 *Shuttle back to Paris*

Aims and Objectives :

After the first two editions organized by the Kavli conferences at Cornell, the 2010 nano-MRI International conference will be held near Paris, France from July 12 to July 16. The goals are to identify the experimental and theoretical breakthroughs that are required to enable magnetic resonance imaging at the nanometer scale as well as the scientific opportunuities open by these near field techniques.

Format :

The format is a four days session in a remote location near Paris with invited talks and posters. Because of space limitation, a selection of the attendees will be performed by the scientif committee, with the aim of bringing the broadest spectrum of scientists together to discuss their current research and build networks with their peers. Ample time for questions and discussions will be reserved to promote the exchange of ideas. The conference will be preceded by a one-day tutorial on MRI microscopy that will be held at the ENS Cachan.

Organization :

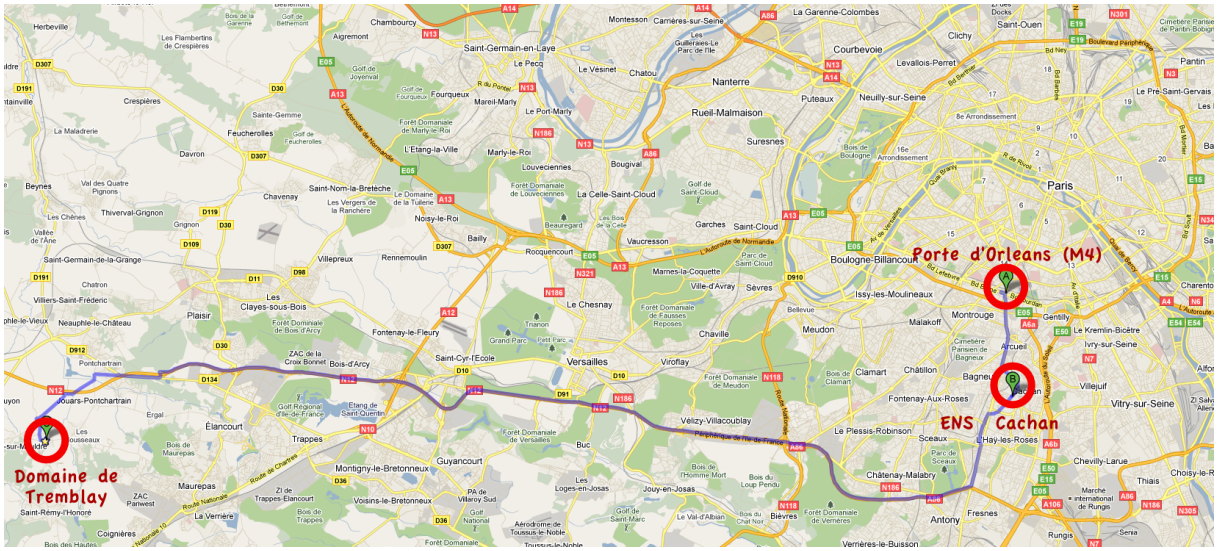
The conference is co-organized by the Service de Physique de l'Etat Condensé (CEA, Saclay) and the Laboratoire de Photonique Quantique et Moléculaire (ENS, Cachan).

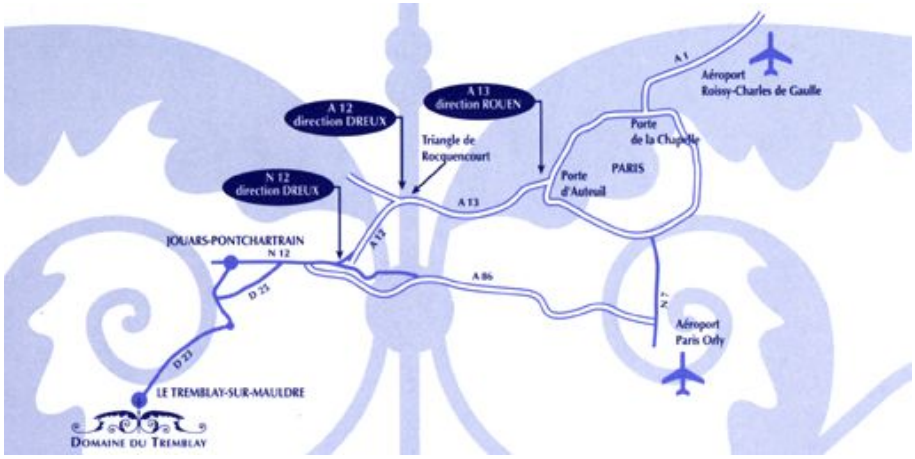
Conference Bus from Paris :

A bus service will be provided to reach the conference site. Two options are offered :

- The bus will be parked at Porte d'Orleans (Metro line 4) close to the gaz station Total (or statue of the Général Leclerc) between 5 :00 and 5 :30 pm on July 12th. The bus company is Hourtoule and it will have the conference logo on the windshield
- The bus will then go to the ENS Cachan to pick up the participants that will attend the tutorial. The bus will then leave the ENS at 6 :00 PM.
- A return bus is also scheduled on Friday July, 16, leaving the conference site at 2 :00 PM for a scheduled arrival at Porte d'Orleans at 3 :00 PM.

If this bus schedule does not fit your travel plan, the best alternative option is to go to Versailles by public transportation and then catch there a Taxi to the Domaine du Tremblay (expected price around 50 €)





A word about history : Domaine du Tremblay

The Castle was built in the early 17^{th} century by Jehan Leclerc du Tremblay, a former councilor of the king Henri III. It still has most of its original appearance today, and it is a nice example of the French architecture of the so-called Louis XIII style. Louis XIII was the king of France from 1610 to 1643 [1], which corresponds to the exact period when the Castle was built. Actually, the history of the Domaine du Tremblay goes back to the 9^{th} century, at the time of Normands incursions in France. Before the 17^{th} century, the general aspect of this place was much more severe, with many defensive elements.
Most of the interior decoration also dates back to the early 17th century : the large wood stairs, the oak doors with decorative sculptures, the painted ceilings "à la française"... In the 18^{th} century, the Castle was extended with two wings and woodworks and a staircase with nice ironworks were added to the decor. From the 19^{th} century, woodworks from the Empire style still remain, and in 1837, a chapel was built in the French classical style so that it fits well with the older buildings around. During this 19^{th} century, most of the Garden "à la française" was also transformed into a more romantic English style garden (90 acres). In 1947 the Domaine du Tremblay was sold to the city of Neuilly-sur-Seine, a wealthy suburb west of Paris. It became again a private property in the 80s. It was then listed in the directory of historical monuments, and was greatly renovated and embellished.

1. Louis XIII was the father of Louis XIV, who built the Palace of Versailles, the most accomplished production of the "Grand Siècle". Its classical style is quite different from the Castle of Domaine du Tremblay, as you will see on Thursday, July 15^{th} afternoon, when a visit of Versailles is planned.

Picnic in Versailles

A visit of the Palace of Versailles is planned on Thursday, July 15th. A bus shuttle will pick us up at Domaine du Tremblay and drop us in front of the Palace at around 2pm. From there, everyone will be free to visit the Palace, the Garden, the Trianon Palaces and Marie-Antoinette's estate during the afternoon. The visit of the Garden is free, individual tickets for the other sightseeing can be purchased on-site, or better, on the web a few days before (http ://billetterie.chateauversailles.fr/online/index.aspx). A picnic will be organised at 6 :30 pm close to the Grand Canal (red cross on the map), where we will meet all together. The Garden closes at 8 :30 pm, and the shuttle back to Tremblay will leave at 9pm (it will take us 20 minutes to walk from the picnic area close to the Grand Canal to the bus shuttle in front of the Castle).
For more informations and a precise map of Versailles, you can have a look at the map which is in your bag and on the web : http ://en.chateauversailles.fr/homepage

Invited Talks

Nanoscale magnetic resonance force microscopy :
Successes, Challenges and Opportunities

Dan Rugar

IBM Research Division Almaden Research Center 650 Harry Rd. San Jose, CA 95120

Magnetic resonance force microscopy (MRFM) achieved a significant milestone in 2008 : the first nanoscale magnetic resonance imaging of a native biological sample. This accomplishment, based on the imaging of hydrogen in tobacco mosaic virus particles, was the result of a succession of improvements in attonewton force sensing, spin manipulation, magnetic tip fabrication and localized rf field generation. Going beyond these initial results will require a dedicated effort to further improve the signal-to-noise ratio of MRFM. In this talk, I review our progress to date, and discuss key challenges and opportunities.

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Beat H. Meier[a]

[a]ETH Zürich, Institut für Physikalische Chemie
Wolfgang-Pauli Strasse 10, CH-8093 Zürich, Schweiz

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NV-Diamond Magnetometry

Ronald Walsworth

Harvard - Smithsonian, 60 Garden Street Cambridge, MA 02138 USA

The detection of weak magnetic fields with high spatial resolution is an important problem in diverse areas ranging from fundamental physics and material science to bioimaging and sensing. Our collaboration at Harvard is exploring magnetic sensors based on optically-detected magnetic resonance of electronic spins associated with nitrogen-vacancy (NV) color centers in room-temperature diamond. NV-diamond is a promising modality for magnetometry because of several fortuitous properties, including long electronic spin coherence times, spin-polarization via optical pumping, spin-state-selective fluorescence, the large Zeeman shift of electronic spin energy levels, and the robust physical properties of diamond in a wide variety of forms (bulk crystals, films, nanocrystals).

CVD Diamond : synthesis, properties and applications

Jean-Charles Arnault

CEA, LIST, Diamond Sensors Laboratory, 91191 Gif sur Yvette, France

Diamond combines outstanding mechanical, electrical, thermal and optical properties. Its high chemical and mechanical resilience, its surface stability, thermal conductivity and wide band gap make diamond a promising candidate for electrochemistry, heat spreaders, biological platforms, sensor devices (MEMS, SAW), tribological coatings.
The Diamond Sensors Laboratory at CEA LIST is involved in the growth of different diamond materials : from CVD single crystals for dosimeters in radiation therapy techniques[1] to ultra-thin nanocrystalline diamond films[2]. More recently, diamond nanoparticles or nanodiamonds (NDs), with size in the range of 5-50 nm, are intensively studied. Their major advantage is their carbon surface, enabling the covalent grafting of different molecules through classical carbon chemistry. A new efficient method to produce fully hydrogenated NDs, directly treated by MPCVD in the gas phase has been recently reported[3]. It provides homogeneous surface terminations for further grafting routes. As NDs can incorporate colour centers, they can act as photoluminescent nano-probes. Beyond these biological applications, NDs are currently used as pre-existing sp^3 carbon seeds allowing the growth of thin diamond films on various substrates[4].
This talk will first focus on the diamond synthesis using CVD techniques. Then, specific properties of single crystal, nanocrystalline diamond films and diamond nanoparticles will be exposed. Finally, major applications for each diamond material will be illustrated.

References

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[3] H.A. Girard et al., *Diam. Relat. Mater.* **19**, 1117 (2010).
[4] H.A. Girard et al., *ACS Appl. Mater. Interfaces*, **1**, 2738 (2009).

Single Defects in Diamond - Towards Sensing and Imaging Single Molecules

Gopalakrishnan Balasubramanian

3. Physikalisches Institut, Universität Stuttgart, D-70550, Stuttgart, GERMANY

Single Nitrogen-Vacancy color centers in diamond are gaining popularity because of its exceptional optical and spin properties. The single spin of the defect can be manipulated optically, providing an efficient way to entangle single electron spins and couple nuclear spin qubits in diamond.[1,2] Long spin coherence time of these single defects finds application as sensitive magnetic field probes. Using engineered diamond we achieve ultrahigh sensitivity, which offers us possibilities to detect single external electron or nuclear spins.[3] By attaching these single spins sensors to the tip of a scanning probe, we were able to perform sensitive scanning probe magnetometry at nanoscale.[4,5] Improving this device by using quantum grade diamond and synchronized NMR pulse sequences we would have the ability to perform nanoscale NMR/MRI of a single molecules. The method has far reaching potential in solving structure of biomolecules under ambient conditions.

References

[1] Gurudev Dutt, M.V. et al., *Science* **316**, 1312 (2007).
[2] Neumann, P. et al., *Science* **320**, 1326-1329 (2008).
[3] Balasubramanian, G. et al., *Nature Materials* **8**, 383 - 387 (2009).
[4] Maze, J. R. et al., *Nature* **455**, 644-647(2008).
[5] Balasubramanian, G. et al., *Nature* **455**, 648-651(2008).

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Dieter Suter

Dortmund University

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Mechanical detection of magnetic resonance using nanowire cantilevers : opportunities and challenges

John Nichol and Raffi Budakian

Department of Physics, University of Illinois at Urbana Champaign

We will describe recent progress using single crystal silicon nanowires for ultrasensitive force detected magnetic resonance. In particular, we will present low temperature non-contact friction measurements and discuss prospects for high resolution nuclear spin imaging.

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Tjerk Oosterkamp

Leiden University

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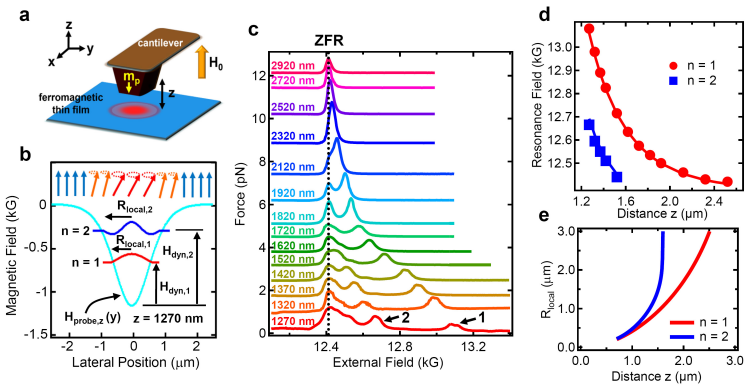
Nanoscale scanned probe ferromagnetic resonance imaging using localized modes

Inhee Lee, Yuri Obukhov, Gang Xiang, Adam Hauser, Fengyuan Yang, Palash Banerjee, Denis V. Pelekhov and P. Chris Hammel

Department of Physics, The Ohio State University, Columbus, OH, 43210, USA

The discovery of new phenomena in multicomponent magnetic devices and expanding opportunities for their application is driving rapid growth in nanomagnetics research. There is an intense need for high resolution magnetic imaging tools able to characterize these complex, often buried, nanoscale structures. Here we report the discovery and demonstration of ferromagnetic resonance imaging (FMRI) through spin wave localization. Conventional ferromagnetic resonance (FMR) provides quantitative information about ferromagnetic materials and interacting multicomponent magnetic structures with spectroscopic precision and is able to distinguish components of complex bulk samples through their distinctive spectroscopic features, however it lacks the sensitivity to probe nanoscale volumes and has no imaging capabilities. Though the strong interactions in a ferromagnet favor the excitation of extended collective modes, we show that the intense, spatially confined magnetic field of the micromagnetic probe tip used in FMRFM can be used to localize the FMR mode immediately beneath the probe. We demonstrate FMR modes localized within volumes with 200 nm lateral dimensions, and straightforward improvements of the approach will allow this dimension to be decreased to tens of nanometers. First images in permalloy films demonstrate that this approach is capable of providing the microscopic images required for the study and characterization of ferromagnets employed in fields ranging from spintronics to biomagnetism. This method is applicable to buried or surface magnets, and, being a resonance technique, measures local internal fields and other magnetic properties with spectroscopic precision.



Identification and selection rules of the spin-wave eigenmodes in spin-valve nano-pillar

Grégoire de Loubens, Vladimir Naletov, Olivier Klein

CEA/DSM/IRAMIS/SPEC, CEA Saclay, 91191 Gif-sur-Yvette, France

Recent progress in spin electronics have allowed the discovery of a new effect, which demonstrates that a continuous current can transfer spin angular momentum between magnetic layers separated by either a normal metal or a thin insulating layer. It leads to a destabilization of the orientation of a magnetic moment induced by a dc spin polarized current. Practical applications are the possibility to control through a current the digital information in magnetic memories or to produce high frequency signals in spin transfer nano-oscillators (STNOs).
From an experimental point of view, the identification of spin-wave eigenmodes in hybrid magnetic nano-structures, and in particular the exact nature of the modes excited by a dc current in STNOs, remains to be done. These modes give a fundamental insight about the nature of the different coupling that might exist between the two magnetic layers. They also influence the high frequency noise of spin-valve sensors.
In order to identify the spin-wave eigenmodes in an individual spin-valve nano-pillar and their selection rules with respect to different excitations, we propose to use the MRFM technique. A first decisive advantage of the MRFM technique is that the detection scheme does not rely on the excitation symmetry. MRFM measures the change in the longitudinal component of the magnetization and therefore it is sensitive to all spin-wave modes that can be excited [3]. A second decisive advantage is that the MRFM is a sensitive technique that can measure the magnetization dynamics in nano-structures buried under metallic electrodes [1,2]. The sample and the magnetic probe attached at the end of a soft cantilever are coupled through the dipolar interaction.
In this work, we perform a comparative study of rf uniform magnetic field and rf current excitations in a perpendicularly magnetized Py(15nm)/Cu(10 nm)/Py(4 nm) spin-valve nano-pillar with a circular section of 200 nm diameter. The magnetization dynamics can be simultaneously detected by MRFM and by measuring electrical voltage through the nano-pillar. Thanks to the preserved azimuthal symmetry of our experiment, unambiguous assignment and labeling of the measured resonance peaks can be obtained by experimental and theoretical means. Adding a dc current through the nano-pillar enables to determine which layer contributes mostly to the observed spin-wave modes, because it produces opposite spin transfer torques on both magnetic layers. The experimentally measured spectra are also compared to micromagnetic simulations, which enable to identify the nature of the coupling between the layers. Three indices are required to label the observed eigen-modes : the usual azimuthal and radial indices for a single disk (l,n), plus an additional index referring to the antisymmetrical or symmetrical (a/s) coupling between both layers. The index (l) related to the azimuthal symmetry of the system plays a particular role as only l=0 modes can be excited by the uniform rf magnetic field, whereas l=1 modes are excited by the rf current due to the orthoradial symmetry of Oersted field. The influence of symmetry breaking (by introducing a tilt angle of the applied magnetic field) on the selection rules is also studied.

References

[1] G. de Loubens *et al.*, *Phys. Rev. Lett.* **98**, 127601 (2007).
[2] O. Klein *et al.*, *Phys. Rev. B* **78**, 144410 (2008).
[3] G. de Loubens *et al.*, *Phys. Rev. B* **71**, 180411(R) (2005).

Diamond magnetometry for low-field NMR at the micro- and nano-meter scale

V. M. Acosta[a], E. Bauch[b], L. J. Zipp[a], A. Jarmola[a,c], M. P. Ledbetter[a],
L.-S. Bouchard[d], and D. Budker[e]

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[e]Department of Physics, University of California, Berkeley, CA 94720-7300

In the last two years a new technique for measuring magnetic fields at the micro- and nano-meter scale has emerged based on optical detection of nitrogen-vacancy (NV) electron spin resonances in diamond [1-3]. This technique offers the possibility to measure magnetic fields from a single electron spin, and perhaps even a single nuclear spin, in a wide temperature range from liquid-helium to well beyond room temperature. Early results have demonstrated the potential of using diamond magnetometers to produce magnetic field maps of samples with unprecedented spatial resolution and magnetic sensitivity opening up new frontiers in biological and condensed-matter [4] research. Sensors employing ensembles of NV centers promise the highest sensitivity [5, 6], and pilot NV-ensemble magnetometers have very recently been demonstrated by several groups, including our own.

We demonstrate a technique to read out the NV spin state using infrared optical absorption at 1042 nm. With this technique, measurement contrast and collection efficiency can approach unity, leading to an overall increase in magnetic sensitivity. We use this technique to operate a dual-channel gradiometer prototype that is well-matched for detection of J-coupling spectra [7] in microfluidic NMR [8] chips. Preliminary measurements at 80 K on a sensor with active area $\sim 50 \times 50 \times 1000\ \mu m^3$ reveal magnetic resonances with amplitude and width corresponding to a shot-noise-limited sensitivity of a few $pT/\sqrt{Hz}$. We also discuss development of a far-field, sub-wavelength, NV-ensemble magnetic nanoscope to study novel magnetic phenomena in condensed matter systems such as vortices in high Tc superconductors.

References

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[3] G. Balasubramanian et al., *Nature Materials* **8**, 383 (2009).
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Concentrative Dynamics Within Forms-and-Flow frameworks for Classical and Quantum Spin Simulations

John Sidles

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Classical spin systems can be simulated by an adaptation of the symplectic dynamical framework that commonly is employed in large-scale molecular simulations. We show how to extend this framework to the quantum domain by introducing three new elements : first, a Lindblad-Ito gauge that concentrates dynamical trajectories onto low-dimension state-spaces ; second, a compatible pullback of symplectic, metric, and complex (Kahler) structures onto those state-spaces ; and third, an efficient algebraic factorization of the compatible state-space structures. The two key physical insights are : (1) thermal processes quench high-order quantum correlations that otherwise are costly to simulate, and (2) the associated concentrative dynamics is naturally described by differential forms and Hamiltonian/symplectic flows. The induced forms-and-flow framework is used to simulate dynamical nuclear-spin polarization (DNP) processes on both classical and quantum state-spaces. Within this framework, simulations of quantum spin systems coupled to thermal baths belong to the same computational complexity class as simulations of classical spin systems.

Diamond surfaces : functional hosts for NV centers

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Imaging and sensing magnetic fields have found key applications in diverse fields such as medical and materials science. For many of these applications, nanometer scaled resolution poses a great challenge. Color centers in diamond, and particularly the nitrogen-vacancy (NV) center, have demonstrated a great potential in magnetic sensing applications. In this respect, the preparation of arrays of NV centers very close to the diamond surface represents an important milestone.
Negatively charged NV (NV^-) centers, in contrast to the neutral NV (NV^0) have been demonstrated to have the most suitable optical and spin properties. Recently, it has been shown that the diamond surface strongly influence the charge state of shallowly prepared NV centers. In this contribution, we will discuss the reversible switch of the charge state of "surface" NV centers. Thus, the electronic and chemical properties of different surface terminations of diamond , such as hydrogen and oxygen termination, will be presented and discussed.

Short Talks

Exploring Methods to Overcome Force Noise in MRFM

John Mamin

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We have previously used MRFM to make 3D images of tobacco mosaic viruses with better than 10 nm resolution. Such measurements were hampered, however, by the considerable loss in quality factor Q (resulting in a rise in force noise) when the sample was brought into imaging range of the magnetic tip. This loss is attributable to a gold coating that was used to promote adhesion of the virus particles and to screen electrostatic fields. In this talk I will describe efforts to develop a new type of coating for virus attachment that has the potential to reduce imaging time by a factor of 10-100. The method involves fabrication of a micron-sized deuterated polystyrene sphere on the end of an ultrasensitive cantilever as a substrate for virus particles, such as tobacco mosaic, cucumber mosaic, and non-infectious influenza viruses. An alternative approach involving synthetic mica substrates will also be presented.

This work was done in collaboration with Dan Rugar, Mark Sherwood, Charlie Rettner, Ginel Hill and Beth Pruitt. Partial support received from the NSF-funded Center for Probing the Nanoscale at Stanford University.

Interactions, fields and dynamics in ferromagnets

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The resonant slice, with a thickness proportional to the line width and inversely proportional to the field gradient, is a very useful concept in EPR and NMR versions of magnetic resonance imaging. However, in this talk I will show that for ferromagnetic resonance (FMR), the resonant slice is a misleading concept, and that a different set of tools is required to understand magnetization dynamics in ferromagnets and ferromagnetic nanostructures. The key feature that differentiates FMR from EPR and NMR is the presence of very strong exchange and dipolar interactions between the spins of a ferromagnet. Because of these strong interactions, it becomes more useful to think of the precessing ÒunitÓ as a collective mode of the magnetization rather than single spin precession. For extended films in uniform fields, analytical solutions for the spin wave eigenmodes are available and publicly available micromagnetic software such as the OOMMF code allow calculations of interactions and dynamic modes in arbitrarily shaped small structures. I will present examples of calculations and measurements of normal modes in ferromagnetic nanostructures highlighting the effects of field gradients arising from the sample magnetization and also from applied field gradients.

Photoluminescent diamond nanoparticles for cellular imaging and traceable drug-delivery into cell

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Nitrogen-Vacancy (NV) color center in diamond has a perfectly stable photoluminescence in the red and near infrared spectral region. Diamond nanoparticles (size $\sim$ 20 nm) containing NV color centers (fluorescent NanoDiamonds, fNDs) are therefore perfectly suited for cellular and tissues imaging in this low absorption window, and for longterm tracking.
We will show that fNDs are spontaneously internalised in different cell lines including primary neurons and does not induce cytotoxicity even at high concentrations. We used fND as a drug delivery vehicle into cell in the context of the treatment of a rare genetic disease (Ewing sarcoma, children bone cancer) by small interfering RNA (siRNA) inhibiting the oncogene expression. siRNA is electrostatically coupled to polycationic polymer coated-fND. We achieved a 50% inhibition efficiency comparable to the one of liposome entrapping strategy, with lower toxicity.

Addressing and creation of single NV in diamond using ion implantation

J. Meijer, S. Pezzagna

RUBION, Ruhr-Universität Bochum

The room temperature quantum device or high sensitive magnetic sensors based on negatively charged nitrogen colour centres (NV^-) centres in Diamond ecomes more and more in focus of researchers all around the world. The fabrication needs a technology that is able to implant single nitrogen ions and a subsequent creation of NV- centres with high production yield. A high lateral resolution implantation method that use an AFM-tip with a small hole like a nanomask is already established in Bochum. Furthermore, the technique is developed for countable single ion using a ion trap source at the group in Mainz. However the subsequent production of negatively charged NV centres for low energetic ion is much more challenging than expected. At high energy the yield is nearby 100% but drops down to zero for low energy implantation ions. We will show a dependency of the yield on the implantation dose and kinetic energy of the ions and discuss models to discuss this behaviour.

Universal dynamical decoupling of single electron spins in diamond

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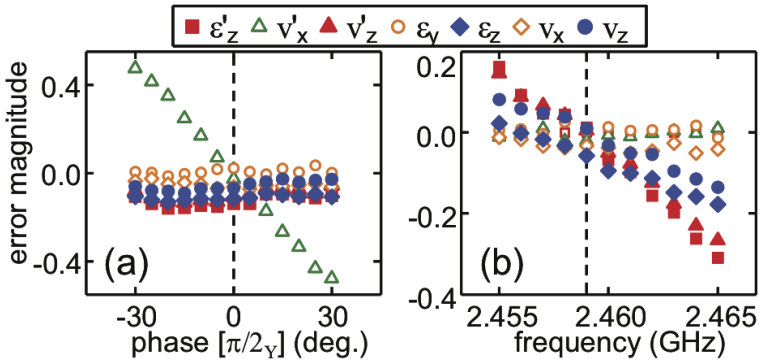
Controlling the interaction of a single quantum system with its environment is a fundamental challenge in quantum science and technology. In magnetometry, the sensitivity for small magnetic fields is limited by decoherence of the probing spin.
We implement high-fidelity quantum control on a single spin in diamond to dramatically suppress its coupling with the surrounding spin bath. Using double-axis dynamical decoupling, we can preserve coherence for arbitrary quantum states. The decoupling universality is verified by quantum process tomography. We finally demonstrate how dynamical decoupling of a spin from its environment can be used to increase the sensitivity of diamond-based magnetometry.



Control of individual nuclear spins in diamond

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Isolated electronic and nuclear spins provide a promising building block for quantum information science, motivating development of techniques to characterize, control, and detect them in suitable systems. The electronic spin associated with the nitrogen-vacancy center in diamond has recently emerged as a leading candidate for a solid-state spin qubit because of its optical spin polarization and long coherence times. Extending the techniques used to control this electron spin, we demonstrate robust initialization, manipulation, and readout of individual nuclear spins in the diamond lattice. These techniques enable precise characterization of nuclear spin hyperfine parameters and coherence properties, and may pave the way for nuclear spin based quantum information architectures in diamond.

Molecular diffusion in micro-MRI : friend or foe ?

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The primary challenge of MRI on the microscopic level is to obtain images with sufficient signal-to-noise ratio (SNR) within a reasonable measurement time[1]. Hence, considerable effort has been invested into optimising RF coils[2] and using high magnetic field strength[3].
Beyond that, at a nominal spatial resolution below about 10 μm conventional MRI techniques are affected by molecular self-diffusion[4]. The associated loss of true resolution can be reduced by using strong gradients. However, this solution decreases the SNR in techniques employing frequency-encoding which favours purely phase-encoded methods such as constant time imaging (CTI)[5]. Using both dedicated hardware and optimised methods so far enabled MRI at an isotropic resolution of 3 ţm, virtually unaffected by diffusion[6].
In contrast, the alternative DESIRE (Diffusion Enhancement of SIgnal and REsolution) approach to micro-MRI utilises diffusion to increase the SNR[7]. Being a real-space imaging method, spatial localisation is accomplished by saturation pulses while diffusion continuously replaces the saturated by unsaturated spins. The effect has been demonstrated experimentally and has a great potential for boosting the SNR in micro-MRI. However, the related image contrast is heavily diffusion-weighted and exhibits an unconventional behaviour in particular in the vicinity of barriers[8]. Hence, the interpretation of DESIRE images is demanding but in return offers the perspective for unique structural information.

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Rotating microcoils for magnetic resonance spectroscopy and microscopy

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Faraday inductive detection remains the most common way to record signals in magnetic resonance. Miniaturized coil have been used during the last ten years in liquids to detect picolitre volumes. Recently, microcoils have been used for solid or generaly anisotropic samples. These samples require spinning in order to obtain high-resolution spectral signatures. Our group has recently introduced spinning microcoils as a means to achieve these requirements.
We are going to present the state of the art in rotating micro-coil technology, and its uses in chemical analysis of anisotropic samples. Recent developments in microscopy using these spinning detectors will also be presented.

Nanoscale diamond magnetometer with quantum-limited sensitivity

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Isolated electronic spins associated with Nitrogen-Vacancy (NV) centers in diamond have been recently proposed as sensitive magnetic sensors. This novel approach to magnetometry is enabled by the good coherence properties of the NV centers, as well as by advanced techniques for their coherent control. The key feature of this solid-state magnetometer is the possibility to confine the sensing spins into a crystal of nanometer size that can be brought extremely close to the magnetic field source, thus achieving high spatial resolution.
The ultimate sensitivity limit is set by the interaction of the spin sensor with its environment and in particular the nuclear and electronic spin bath. Engineering, controlling or harnessing the environment can lead to better sensitivity. In this talk I will present two strategies for beating the standard quantum limit in magnetic sensing.
NV-NV couplings that usually limit the sensitivity could be used instead to create a squeezed state, yielding enhanced sensitivity. Squeezing can only be achieved by using coherent control to engineer the desired Hamiltonian, while protecting the system from decoherence. A different strategy exploits instead part of the spin bath (paramagnetic nitrogen spin impurities) to improve the sensitivity without the need of large squeezed states. The bath spins are used as ancillas to amplify the system's response to the external field, prior to detection via the optically active electronic spin qubit.
Finally, I will outline exciting applications enabled by the improved sensitivity in areas ranging from bio- and materials science to single electronic and nuclear spin detection.

NV nanodiamond decoherence detection of spins in solution

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Monitoring the decoherence of a NV qubit probe in response to changes in environment may provide a novel and sensitive measurement of fluctuating magnetic fields at the nanoscale. We report theoretical and experimental results exploring this idea. In particular, we have immersed nanodiamonds in various aqueous solutions and find that the coherence of the NV system measured by spin-echo is preserved under ambient conditions. Following these control experiments, immersion in a spin-rich environment resulted in a significant change in the decoherence of the NV centre. A detailed theoretical analysis of the spin-echo data was carried out exploring the response of the NV nanodiamond system to Mn ions at or near the nanodiamond surface.

Force-gradient detection of electron spin resonance from a nitroxide spin label : A path to applications

John A. Marohn[a, 1], Eric W. Moore[a], SangGap Lee[a], Jonilyn G. Longenecker[a], Steven A. Hickman[a]
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Force-gradient methods for observing magnetic resonance using attonewton-sensitivity cantilevers have dramatically increased the range of detectable materials [1]. Recent experiments at Cornell extend force-gradient detection of electron spin resonance to include the nitroxide spin probe TEMPAMINE, whose spin-lattice relaxation time is only T1 1 ms [2]. We achieved a sensitivity of 400 mB in vacuum at a temperature of 4.2 K, in a field of 0.6 T, and using a 4 ?m diameter nickel tip affixed by hand to a high-compliance cantilever. This is an exciting result because nitroxide spin probes are widely used to study the tertiary structure of materials in the bulk, in membranes, and at surfaces. Moreover, attachment chemistry has been established for affixing nitroxide spin probes to carbohydrates and polymers, proteins, and nucleic acids. In this talk I will describe our efforts to detect electron spin resonance from a single nitroxide spin label.
Our detection approach has a number of attributes that make it well suited for a single spin experiment. We detect Boltzmann polarization instead of spin fluctuations [3], allowing us to average signal amplitude instead of signal power, with signal to noise improving in the usual way, proportional to the square root of the number of averages. The method modulates magnetization via saturation and does not require spin locking, potentially lowering the required microwave power. Surface frequency noise is typically observed to be larger than force noise near a surface, however, which is a concern with our method. To address this concern, we introduce and demonstrate via ESR-MFRM a method for reading out a spin-induced spring constant shift as a change in cantilever amplitude. In this method the spins act as a non-degenerate parametric amplifier ; the detection of a spin-induced spring constant shift is now in theory limited by the force noise and no longer by the frequency noise. By working with the magnet on the cantilever, we hope to harness sample-preparation protocols, such as flash freezing, that have been developed for cryo electron microscopy. We will present cantilevers with integrated 100 nm diameter nickel tips which maintain 10 aN $\mathrm{Hz}^{-1/2}$ force sensitivity down to tip-sample separations as small as 3 nm. Taken together, these findings suggest the feasibility of using MRFM to determine the tertiary structure of an individual biomacromolecule or macromolecular complex at reasonable averaging times by directly imaging the location of electron spin labels attached to it.

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Towards nano-MRI and in mesoscopic transport systems

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Universität Basel

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Magnetoresistive hybrid sensors for very low-field MRI

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Magnetoresistive hybrid sensors can detect magnetic signal in femtotesla range competing with SQUIDs technology. These sensors are the combination of a field Giant Magnetoresistive (GMR) sensor and a flux-to-field superconducting transformer. Their response is flat in frequency and hence, their sensitivity becomes better than resonant coils at low frequencies. Main advantages of these sensors are their robustness against external static fields and fast recovery after RF pulses. One main interest of mT field MRI is the variation of contrasts in this field (frequency) range. We have developed a small MRI system working with static fields up to 8mT. We will present first results obtained and perspectives.

Near-field scanning single-photon microscopy with an individual NV-center : some possible applications

Serge Huant

Institut Néel

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Poster

Use of the SPAM geometry, CERMIT protocol, and sample shuttling in MRFM

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We describe an MRFM probe built by the authors using the SPAM (Springiness Preservation by Aligning Magnetization) geometry. The probe operates at 5 K, up to 9 T, has 3D sample stage motion, and spring based vibration isolation yielding Brownian motion limited behaviour. Using 5-10 um diameter Ni spheres mounted on Cornell University fabricated cantilevers with spring constants of 1.0 to 0.1 mN/m and the CERMIT (Cantilever Enabled Readout of Magnetic Inversion Transients) protocol we describe the probe's performance, inc., Brownian motion and frequency deviation noise behaviour, the cantileverÕs frequency and Q dependence vs. background magnetic field, power density spectra of cantilever fluctuations both far from and near to a gold coated GaAs surface, and NMR line shapes of Ga69.

The SPAM geometry was invented by John Marohn to overcome limitations of the hang-down geometry. The magnetic particleÕs magnetic moment remains parallel to the background magnetic field, avoiding the magnetic field contribution to the cantileverÕs spring constant and eliminating microhysteresis losses. This enables using magnetic particles a few microns in diameter, as needed for imaging whole cells. We will present data showing these advantages are not realized by all magnetic particles.

Using the CERMIT protocol we are able to measure the real time recovery of the polarization during an inversion-recovery experiment by monitoring the frequency of the driven cantilever. The initial Ga69 polarization is inverted with a 20 msec, 400 kHz wide ARP (Adiabatic Rapid Passage) sweep through the bulk peak. The RF is on only during the 20 msec. After inverting the polarization we observe the initial -50 mHz transient decay back to the base line as the polarization realigns along the Zeeman axis with a T1 of approximately 20 minutes.

Magnetic resonance spectroscopy requires uniform magnetic fields which seems incompatible with the large magnetic field gradients in MRFM. Shuttling the sample away from the magnetic particle to reduce the magnetic field inhomogeneities resolves this apparent contradiction. At a large sample-magnetic-particle separation the desired spectroscopic pulse sequence is applied to the sample and one point on the free induction decay is stored along the Zeeman-axis. The sample is then shuttled back to the close proximity of the magnetic particle where the magnetization stored along the Zeeman-axis is read out. By repeating this process the entire free induction decay can be recorded. We have undertaken a program to implement shuttle based spectroscopy. Progress in NMR spectroscopy of strained GaAs via sample shuttling will be reported.

Experiments using Force Detected Nuclear Magnetic Resonance [1] [2]

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We describe experiments using force detected nuclear magnetic resonance (NMR). We have developed a helium-3 system for high sensitivity measurements. An initial room temperature scan of $(NH_4)_2SO_4$ demonstrated 1-D resolution of 10 μm ; a spin nutation experiment in this probe determined the value of the rotating magnetic field to be 13 gauss, and a spin echo was observed with a full width at half maximum of 8 μs. At 77 K we obtained the first force detected boron NMR signal in a 30 μm powder sample of the superconductor MgB_2.
In addition, we describe the construction of a compact room temperature probe with versatile positioning capabilities. We plan to initially study NH_4PF_6 because of the high density of hydrogen and fluorine, both of which can be easily detected using this technique ; furthermore, cross-polarization to enhance the weaker phosphorous magnetization can be achieved. This probe will also be used to perform dynamical imaging experiments on liquids, initially using samples which have been calibrated with conventional NMR. These samples will be studied at different temperatures. Later, we want to study temperature-dependent effects on the local T_1 and T_2 of complex samples.
We also describe a variable temperature probe for both micro-crystal NMR and dynamical imaging experiments. This probe is currently being used to further study and to map the spin lattice relaxation as a function of temperature of MgB_2 to elucidate the pairing symmetry as well as effects due to its two nearly independent electronic bands.

1. NSF Grant Nos. DMR-0605828 and DGE-0549417
2. Welch Foundation Grant No. F-1191

Custom Atomic Force Microscope for Scanning Diamond Magnetometry

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There has been an increasing interest in using diamond-based sensors to perform high resolution and sensitivity scanning magnetometry. Implementing this design for general and non-transparent samples is difficult as commercially available AFM instruments do not allow optical monitoring of the cantilever tip and collection of fluorescence with a high-NA objective from the same side. We describe a custom scanning magnetometer design that will be compatible with any type of sample. The AFM has a large open bottom and top and provides dual optical access. The deflection from the cantilever is measured by optical beam deflection and so that a wide range of commercial cantilevers can be used. The AFM and the confocal microscope objective can be locked in position while a piezoelectric stage that allows raster scanning of the substrate. With this AFM design, we will attach single NV defect to the cantilever tip and use it for nanoscale magnetic imaging.

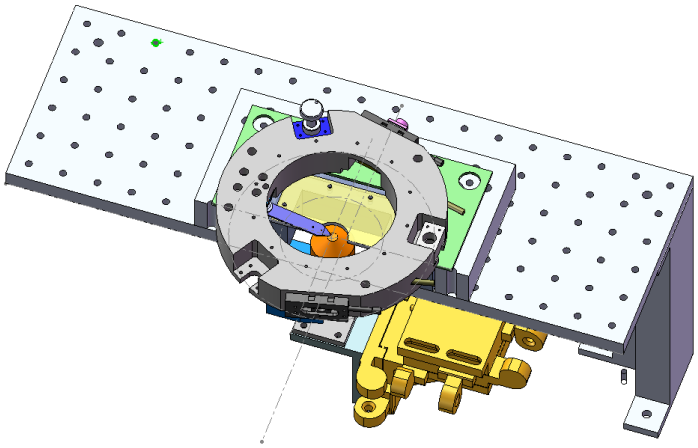

FIGURE 1: Schematics of the custom AFM design

Voltage sensing by nanodiamonds and other N-V trickeries

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Cell usually show an electric potential of on the order 100mV between the in- and outside. This "membrane potential" is essential to maintain ion balance in the cell, and is important for signals transmission in neurons. In this talk we will evaluate the possibilities for nanodiamonds with single N-V centers to measure membrane potentials via the electric Stark shift of the 2.9 GHz magnetic resonance transition, thus serving as "voltage sensitive dyes". We will then shift our focus to the measurement of small magnetic fields, and discuss strategies to use the N-V center for recording high-resolution spectra of nuclear spin fluctuations.

Nanoscale electric field sensing with a single spin in diamond

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We study the linear stark effect of a single nitrogen vacancy center in diamond (NV). The unique properties of the NV allow optical detection of magnetic resonance (ODMR). We use the spin of a single NV as a nano scale electric field sensor. Using pulsed experiments long coherence times are reached, such that the phase difference induced by an alternating electric field can be detected. We reached shot noise limited detection of the electric field. The nano scale sensing of electric fields has a wide range of applications in biology and material sciences.

Evading surface and detector frequency noise in harmonic oscillator measurements of force gradients II : Theory

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We present theoretical signal and noise calculations for a protocol we have developed using parametric amplification to evade the inherent tradeoff between signal and detector frequency noise in force-gradient MRFM signals, which are manifested as a frequency shift of a high-Q microcantilever. Sample-induced frequency noise has a f^{-1} frequency dependence, while detector noise exhibits an f^2 dependence. Operation at the frequency that minimizes the sum of these two contributions typically results in a surface frequency noise power an order of magnitude or more above the thermal limit and may prove incompatible with sample spin relaxation times as well. We show how the frequency modulated force-gradient signal can be used to drive the fundamental resonant mode of the cantilever, resulting in an audio frequency amplitude signal that is readily detected with a low-noise fiber optic interferometer. This technique allows us to modulate the force-gradient signal at a frequency sufficiently high that sample-induced frequency noise is negligible without subjecting the signal to the normal detector noise of conventional demodulation protocols.

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Sample container for watery samples

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Magnetic resonance imaging (MRI) provides spatial images with high information content through various contrast techniques. Magnetic resonance force microscopy (MRFM) can extend the spatial resolution of MRI to the nanometer range[1]. As in MRI, spectral information, for example dipolar[2,3] or quadrupolar[4] couplings and the chemical-shift[5], which provides detail information about the chemical composition, can be used to realize image contrast.
To achieve high Q factors, the MRFM cantilever for detection must be placed in a high vacuum. This limits the possible samples for MRFM and wet samples have not yet been detected. We propose a room temperature MRFM design that should allow extending the measurable samples for MRFM. The sample will be vacuum protected by placing into a sample container with suitable window. The ferromagnetic tip placed on the cantilever is under vacuum condition and can be approached close to sample staying behind the window under ambient conditions. RF is created by a strip line design.
This setup should allow localized spectroscopy for a gradient-on-cantilever setup. Spatial encoding will be achieved by spatial Hadamard encoding.

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Critical magnetization fluctuations observed by frequency-shift cantilever torque magnetometry

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Quantifying both the average moment and magnetic fluctuations of individual nanometer-scale ferromagnets is critically important for pushing magnetic resonance imaging to atomic resolution via mechanical detection. Attonewton-sensitivity cantilevers enable torque magnetometry to detect both the average moment and magnetization fluctuations with unsurpassed sensitivity. Most cantilever magnetometry studies have examined in-plane switching. We used ultrasensitive cantilever torque magnetometry to examine in-plane to out-of-plane magnetization switching of individual nickel nanorods at T = 4.2 K. Here we report observing three new magneto-mechanical phenomena $\tilde{N}$ sharp, simultaneous transitions in cantilever frequency, quality factor, and frequency jitter $\tilde{N}$ associated with the switching of individual domains in the nickel nanorod. We present a model which semi-quantitatively accounts for these phenomena. Our results show that mechanically detecting in-plane to out-of-plane magnetization switching of individual domains is a promising new approach to examining magnetization fluctuations and, potentially, to sensitively detecting magnetic fields with nanoscale spatial resolution.

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Integration of batch-fabricated overhanging magnet tips on attonewton-sensitivity cantilevers

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Achieving atomic resolution in magnetic resonance force microscopy (MRFM) requires using cantilevers with a low minimum detectable force F_{min} at small tip-sample separations and fabricating magnetic tips with only a few nanometers of damage at the leading edge. We address these challenges by 1) fabricating cantilevers with overhanging magnetic tips that achieve F_{min}=10 aN at 4.2 K and tip-sample separations of 3 nm, 2) protecting the nanomagnet leading edge by atomic layer deposited (ALD) alumina to suppress nickel oxide formation, and 3) characterizing the extent and chemical mechanism of damage by nanometer-resolution electron energy loss spectroscopy (EELS). By EELS analysis we determined that there was 20 nm of nickel oxide damage at the magnet leading edge, which allowed for closer tip-sample separations than were previously possible. By introducing interdiffusion barriers to our forty-two step fabrication process, we demonstrate the reduction of damage layer thicknesses. A thin sacrificial ALD alumina layer is deposited over the nanomagnets during processing, significantly reducing the formation of nickel oxide at the exposed magnet surfaces, and tantalum is deposited under the nickel magnets, which prevents nickel silicide formation at the nickel-silicon interface. The nanomagnet grain structure, point-by-point relative atomic concentrations at the leading edge, and magnetization are determined by high-resolution transmission electron microscopy (TEM), EELS, and frequency-shift cantilever magnetometry, respectively. Our findings suggest that fabricating a cantilever suitable for single proton detection, while a materials processing challenge, should be possible.

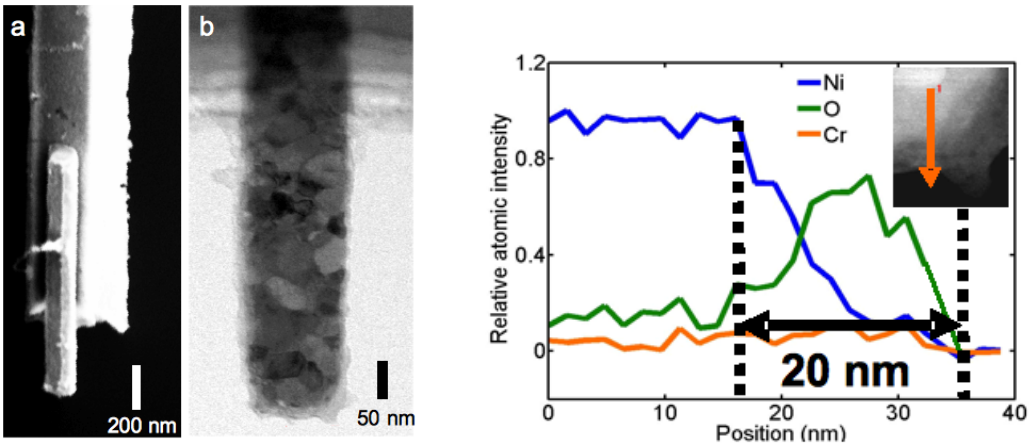

FIGURE 1: Left : (a) SEM and (b) TEM images of overhanging nickel-tipped nanomagnets. Right : EELS analysis of the leading edge of an unprotected nickel nanomagnet (see inset) showing 20 nm of damage.

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Magnetic Properties of Thin Film Edges Measured Using Localized Ferromagnetic Resonance

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The qualities of the edges of patterned thin films are important, especially in magnetic nanostructures where the edges often provide the nucleation point for magnetization reversal and/or vortex formation. A simple geometrical argument says that the properties of the material at the film edges become more important relative to the bulk properties as devices are scaled down. Here, we present a ferromagnetic resonance technique that uses localized spin wave modes to characterize magnetic properties of the patterned film edge, and we review the measurements that have been made using this technique.

The samples used in these measurements are large arrays of straight, parallel stripes. With magnetization saturated in plane and perpendicular to the stripe axes, strongly inhomogeneous magnetostatic fields provide a low-field region near the edges where precession of the magnetization is localized within approximately 30 nm of the edge in and edge mode. The field dependence of the edge mode frequency yields the magnetic properties of the edge, primarily, the field required to saturate the magnetization perpendicular to the edge. Using this technique, we have shown in a series of papers how the properties of $Ni_{80}Fe_{20}$ film edges depend on side-wall angle[1], film thickness[2], oxidation[3] and interactions within multilayers. In all of these measurements we use comparisons with micromagnetic modelling of edge modes at ideal and non-ideal edges[4].

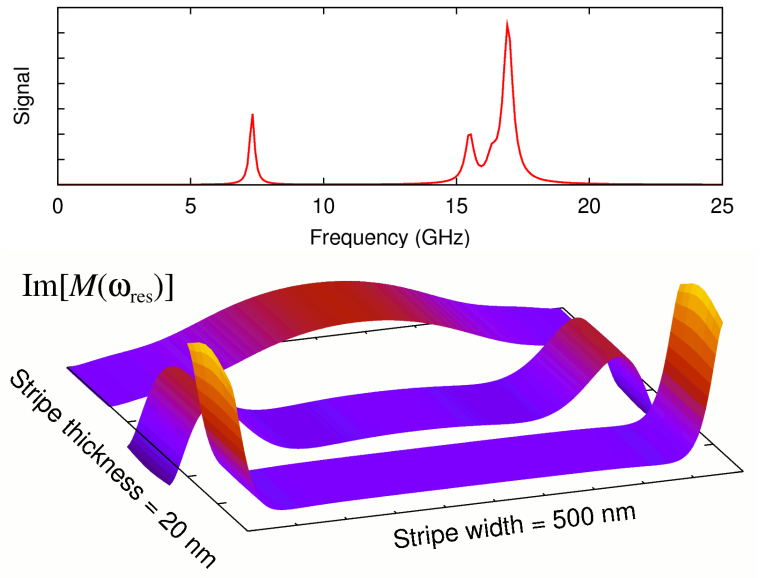

FIGURE 1: Top : Modelled spectrum of a stripe with an edge mode resonance at low frequency Bottom : Corresponding mode profiles. The edge mode is localized at the edges of the s

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Characterization of random AC magnetic fields using a single Nitrogen-Vacancy center

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We report on the use of a single Nitrogen-Vacancy (NV) center in diamond as a magnetometer to probe asynchronous oscillating magnetic fields. Using engineered currents to induce random fluctuations in the field amplitude and/or phase, we observe the NV center optical response as a function of field intensity. Processing the measurement record of fluorescence intensities from successive NV observations, we reconstruct the correlation function of the source field and, from it, the corresponding spectral density. We use this framework to characterize the śpin noiseźrom the surrounding bath of ^{13}C nuclei. In agreement with theory, we find that the NV fluorescence variance is maximum when the spin-induced field fluctuation cancels after a full ^{13}C precession in an external dc magnetic field. The latter leads to a pattern of variance ŕevivalsídentical to that observed when monitoring the average fluorescence. We fail, however, to identify the signature of ^{13}C Larmor precession in the resulting spectral density, perhaps an indication that the correlation time of the ^{13}C spin bath is shorter than expected.

Quantum Point Contact as a displacement detector of cantilever motion

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Evading surface and detector frequency noise in harmonic oscillator measurements of force gradients I : Experiment

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Spinometers as Thermostatic Measurement, Measurement & Controllers, Using Compact Algebraic Representations to Simulate Photon Counting

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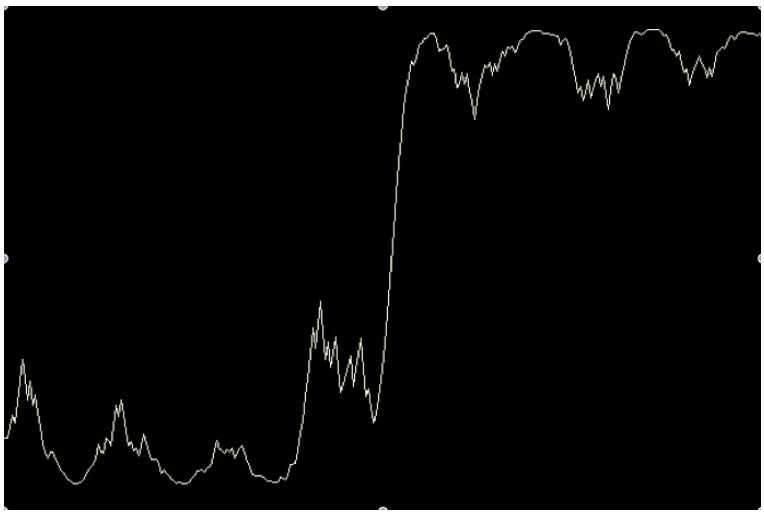
Spinometers are a simulation of interacting thermal baths. These interactions are commonly known as "thermostatic" flows, and this implementation is written as a Java applet.
The first thermostatic relation between two thermal baths can be termed measurement. Measurement is equivalent to control processes, and hence we can ÒtuneÓ the interaction in x, y, and z channels. The resulting simulation, shown as a trace output for x, y, and z dimensions on an oscilloscope, is indistinguishable from nature. Simulating this interaction can be done in compact algebraic representation; the$i$th simulated measurement of the system is $c_i^T\ \sigma$, where c is defined as follows :

$$c_0 = \begin{pmatrix} 1 \\ -1 \end{pmatrix} \cdot \frac{\sqrt{2}}{2} \tag{1}$$

$$c_i = \begin{cases} \dfrac{A(c_{i-1})}{\sqrt{p}}, & \text{with probability } p = (Ac_{i-1})^T(Ac_{i-1}) \\ \dfrac{B(c_{i-1})}{\sqrt{1-p}}, & \text{with probability } 1-p \end{cases} \tag{2}$$

Where $A = 1((cos(\theta) + i)I + sin(\theta)i\sigma)$ and $B = i((cos(\theta)?i)I + sin(\theta)\sigma)$. A and B matrices are precomputed for each dimension; θ_x,θ_y, and θ_z are given as parameters of the simulation, and σ_x, σ_y and σ_z are defined as $\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$, $\begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$ and $\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$ respectively.
This simulation demonstrates the equivalent natural process of a two-state system, in which a photon is sent along optical fibers to one of two detectors. By making measurements, we force the state to change; an example of this change in state can be seen in the z-channel of the simulation (simulation output below).



Outline for a Graduate Degree Program in Computational Engineering

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We have developed an outline for the necessary syllabus to support a graduate degree program in Computational Engineering.
This poster outlines a syllabus for conferring that level of knowledge in an interdisciplinary program. Materials are presented in lectures and readings to solve problems in the form of a Mathematica notebook duplicating calculations of a Forms-and-Flow Frameworks.
The Forms-and-Flow Frameworks works through Arnoldś Classical Mechanics and Neilsen and Chuangś Quantum Computation and Quantum Information. We work through these texts backwards, covering metric/symplectic geometric structures first, then unwinding through quantum Hamiltonian dynamics, classical Hamiltonian dynamics, Langrangian dynamics, and Newtonian dynamics.
The emphasis is on mathematical and software tools for the pullback of dynamical functions and forms, and the pushforward of dynamical vectors and curves. Weŕe using Mathematica as the interactive graphical front-end of a Knuth-style, nuweb-based literate programming environment, whose output is MATLAB source files and LaTeX documentation.
We will also present applications of forms-and-flow frameworks in applications for disciplines in physics, chemistry, biology, math and engineering. The objective is to translate recent fundamental research in quantum spin biomicroscopy, and in quantum simulation theory, into education tools that support a Computational Engineering Masterś Degree.
This is to be understood as a simultaneous link-up of :
– Mathematical tools

– Nanotechnology

– Bio-imaging and genomic applications

in which technology-building, team-building, and confidence-building are of equal importance. It is envisioned and intended that forms-and-flow frameworks will play a role similar to that of computational fluid dynamics in the missile program, and shotgun reconstruction in the genome program.

Selective production of NV- in electron-irradiated nanodiamonds

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For several years, negatively charged centre (NV^-) of diamond has drawn much attention because of its great optical properties (perfect photostability, high quantum yield) and its unique spin properties. Nanodiamonds containing NV^- could be used in numerous fields such as for the development of single photon source, biolabels, nanoprobes for magnetometry. NV^- centres can be produced either by nitrogen implantation or by electron/protron irradiation. However, these processes also lead to the formation of neutral centres (NV^0), which are of no interest for electron spin-based applications. The development of a method to produce selectively NV^- centres in nanodiamonds would be a significant breakthrough.
We present here the evolution of the ratio NV^-/NV^0 in nanodiamonds created under high-energy ($\sim$ 14 MeV) electron irradiations. After annealing, individual nanodiamonds were characterized using confocal microscopy coupled with atomic force microscopy. We studied the NV^-/NV^0 ratio according to the irradiation dose and the nanodiamond size. We evidence that a change of the irradiation dose does not modify the NV^-/NV^0 ratio. However, the size of the irradiated nanodiamonds plays a significant role : NV^- centres are preferentially created in large nanodiamonds, probably because of surface effects. For nanodiamonds bigger than 60 nm, NV^- centres are nearly exclusively formed. In order to get NV^--containing nanodiamonds smaller than 60 nm, we investigated thermal oxidation process.

Widefield magnetic imaging using an array of spins in diamond

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We present a solid-state high sensitivity magnetic field imaging technique using an array of spins in diamond. In addition to remarkable sensitivity and vector imaging other salient features of this technique are wide area imaging with high spatial resolution and functionality under ambient conditions. The sensing spin array is made of Nitrogen-Vacancy (NV) color centers in diamond probed by Optically Detected Magnetic Resonance (ODMR). These NV centers created at shallow depths on the diamond surface are used to image the spatial and temporal variations of magnetic fields in their close proximity. The Zeeman splitting of the NV spin states is readout optically in a multiplexed manner using a CCD camera over a 60x60 μm field of view with a spatial resolution close to 250 nm. We experimentally demonstrate full vector imaging of the magnetic field produced by a pair of current carrying micro-wires. The high magnetic sensitivity together with high spatial resolutions and operability under physiological conditions offers the potential to image proton densities, hence Magnetic Resonance Imaging (MRI) on live cells with sub-cellular resolutions.

Spin properties of defects in single digit nanodiamonds

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Matchless photostability, magnetic resonance at room temperature combined with chemical inertness and excellent biocompatibility, put nanodiamonds with single color centers in the focus of interest for new high resolution microscopy methods. An example for such color center is the NV-center. Through progress in irradiation and milling we achieved fluorescent nanodiamonds with sizes below 4 nm containing single defect center [1]. Recent research showed that even very small nanodiamonds with NV-center retain their optical and spin properties [2]. Based on these new findings novel high resolution imaging could be performed by field gradient magnetometry. For the method a nanodiamond with a single NV color center was placed on the tip of an atomic force microscope combined with a confocal fluorescence microscope. With the new particles it is now within reach for magnetometry to get below the already achieved magnetic field limit of 5 mT [3].

References

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Two-dimensional MRFM Images of Polymer Blends using full-volume Fourier and Hadamard encoding

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It has already been demonstrated[1] that two-dimensional MRFM imaging using full-volume Fourier and Hadamard encoding robustly works for salt crystals. They imaged a test sample made out of $(NH_4)_2SO_4$ with a resolution of 1μm. This is the desired range to resolve different polymer phases in polymer blends. Therefore MRFM could be an alternative to AFM (which is bound to the surface) with the advantage of being a full 3D technique.
The challenging task to detect polymers with 'conventional' MRFM (detection of amplitude modulated Zeeman polarization) is their short $T_{1\rho^\star}$ relaxation time (ca. 30ms) compared to previously used salt crystals (ca. 1s). This results in a severe signal loss because the signal-to-noise ratio is proportional to the square root of the relevant relaxation time : SNR $\sim \sqrt{T_{1\rho^\star}}$.
We present a two-dimensional image of a polymer blend containing two different polymer phases : PTFE (Polytetrafluoroethylene) and PEEK (Polyetherketone) resolved by ^{1}H(PEEK)^{1}9F(PTFE)-nuclei-contrast. The achieved resolution in z-direction is $\tilde{5}$00nm which is encoded by the Zeeman frequency of the spins in the inhomogeneous magnetic field produced by an iron cobalt cylindrical gradient source. In the x-direction the field gradient of the rf-pulses is used to encode the position. This rotating frame encoding obtains a resolution of $\sim 2\mu$m.

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Cooling cantilevers to millikelvin temperature

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The force sensitivity of Magnetic Resonance Force Microscopy is currently limited by the thermo-mechanical noise of the cantilever sensor. We are exploring the possibility of substantially improving the sensitivity by cooling the cantilever to millikelvin temperature. In order to prevent light-induced cantilever heating, which limits the lowest temperature achievable using conventional interferometers, we have developed an alternative SQUID-based detection scheme. We present measurements of the thermal noise of an ultrasoft magnetic tipped silicon cantilever down to an effective temperature of about 25 mK, which corresponds to a force sensitivity of 0.5 aN/$\sqrt{Hz}$. The experiment has been performed in vacuum in a cryo-free pulse-tube dilution refrigerator. We discuss residual heating in the present setup and possible additional heating effects that could be critical in a real MRFM experiment.

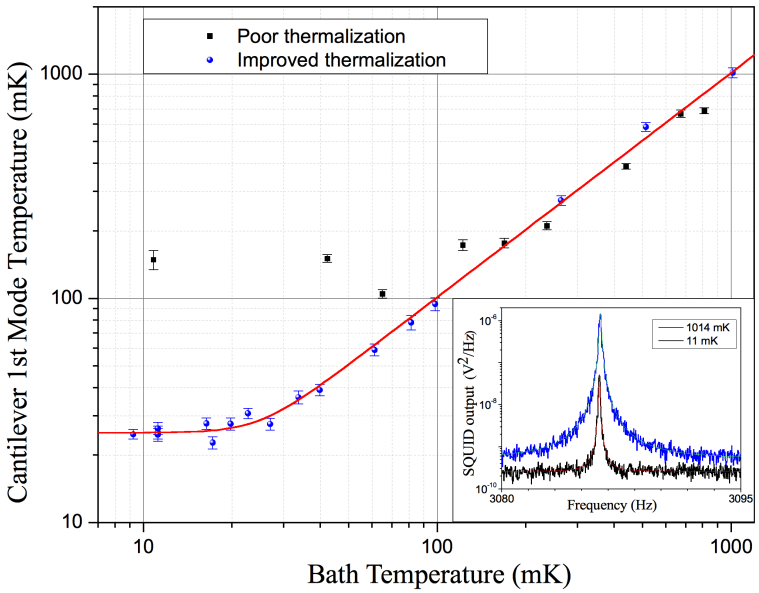

FIGURE 1: Noise temperature of the first cantilever mode as function of the bath temperature. In the inset, power spectral density around the mode at bath temperatures of 1.01 K and 11 mK

High Sensitivity Magnetic Sensing By Ensemble Measurements On Densely Packed Defect Centers in Bulk Diamond

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Single, fluorescent defect centers in diamond have drawn much attention during the last few years. Namely the spin properties of the NV-center, its remarkable photo-stability and its sensitivity towards magnetic fields led to numerous scientific contributions in apparently very different areas of application, e.g. quantum computing and spintronics[1], fluorescence and high resolution optical microscopy[2] and magnetometry. In this work we present approaches towards high sensitivity magnetometry using ensemble measurements on densely packed NV-centers in bulk diamond at room temperature. Using EPR manipulation techniques with optical detection spin states of the NV-centers can be changed and read out. Changes in the spin state of single NV-centers are sensitive to external magnetic fields (Zeeman effect). The sensitivity of these measurements scales with the squareroot of the number of NV-centers probed[3]. For a single NV-center magnetic a sensivity of $3\mathrm{nT/Hz}^{-1/2}$ has been shown. Ensemble measurements in densely packed bulk diamonds give the opportunity for high sensitivity magnetic sensing with sensitivities in the range of $10^{-15}\mathrm{T/Hz}^{-1/2}$ while keeping the dimensions of the sensor small to probe local magnetic fields and can be implemented in principal in miniaturized devices.

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Pushing MRFM sensitivity boundaries using SQUIDs

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We are working towards increasing the magnetic moment sensitivity of Magnetic Resonance Force Microscopy (MRFM) experiments by using a SuperConducting Quantum Interference Device (SQUID) to detect the motion of the cantilever. This novel detection scheme will enable us to measure spin signals at millikelvin temperatures while keeping the back-action noise at a minimum. For the SQUID detection scheme it is necessary that the detection magnet, which also creates the field gradient necessary for MRI, is placed on the cantilever. The motion of this magnet leads to a flux change in a sensor coil that surrounds the studied spin sample. Via a transformer the flux change is then measured with a SQUID. Using this detection scheme, we have already been able to observe the thermal motion of a cantilever at an effective temperature of 25 mK, corresponding to a force noise of 0.5 aN/$\sqrt{Hz}$. With a 1-dimensional approach system we were able to tune the coupling between the sensor coil and the detection magnet. Future steps involve adding an RF wire in order to perform the first NMR and ESR measurements and implementing a 3-dimensional approach and scanning mechanism to enable spin imaging.

Index of Contributions

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