ESM2019: EXPERIMENTAL TECHNIQUES

The EUROPEAN MAGNETISM ASSOCIATION

CEITEC

THE EUROPEAN SCHOOL ON MAGNETISM

#BRNOREGION

PROGRAM TIMETABLE

MO 2/9

8:00 - 9:00 Breakfast
13:00 - 14:30 Lunch
15:00 - 15:30 Urbanek Opening
15:30 - 17:00 **Fruchart:** Fields, moments units
17:00 - 20:00 Welcome

TU 3/9

8:00 - 9:00 Breakfast
9:00 - 10:30 **Simonet**: Magnetism of atoms
10:30-11:00 Coffee
11:00 - 12:30 **Abelmann:** Magnetic interactions
12:30 - 13:00 Poster clips
13:00-14:30 Lunch
14:30 - 15:00 Q&A
15:00-19:00 Practicals
19:00-22:00 Brno guided tour

WE 4/9

8:00 - 9:00 Breakfast
9:00 - 10:30 **Abelmann:** Ordering, mean field
10:30-11:00 Coffee
11:00 - 12:30 **Jungwirth:** Transport I
12:30 - 13:00 Poster clips
13:00-14:30 Lunch
14:30 - 15:00 Q&A
15:00-19:00 Practicals

TH 5/9

8:00 - 9:00 Breakfast
9:00 - 10:30 **Fruchart**: Magnetization processes
10:30-11:00 Coffee
11:00 - 12:30 **Jungwirth:** Tranport II (memory devices)
12:30 - 13:00 Poster clips
13:00-14:30 Lunch
14:30 - 15:00 Q&A
15:00-19:00 Practicals

FR 6/9

8:00 - 9:00 Breakfast
9:00 - 10:30 **Schaefer:** Magneto optics
10:30-11:00 Coffee
11:00 - 12:30 **Simonet:** Neutron scattering
13:00-14:30 Lunch
14:30 - 15:00 Q&A
15:00-16:30 **Schaefer/ Sebastian:** Industrial Perspectives
18:00-20:00 Poster Session

SA 7/9

8:00 - 9:00 Breakfast
9:00 - 10:30 **Rasing:** Pump probe
10:30-11:00 Coffee
11:00 - 12:30 **Fruchart:** Spin sensitive SPM
13:00-14:30 Lunch

14:30 - 15:00 Q&A
15:00-19:00 Sport afternoon

SU 8/9

8:00 - 9:00 Breakfast
9:00 - 10:30 **Rasing:** All optical switching
10:30-11:00 Coffee
11:00 - 12:30 **Luning:** X-ray techniques
13:00-14:30 Lunch
14:30 - 15:00 Q&A
15:00 - 16:30 **Luning:** X-ray holography

MO 9/9

8:00 - 9:00 Breakfast
9:00 - 17:30 Excursion to Moravský Kras (hiking and caves)
17:30-19:00 Brewery Excursion

TU 10/9

8:00 - 9:00 Breakfast
9:00 - 10:30 **Lubk:** Electron spectroscopy and microscopies
10:30-11:00 Coffee
11:00 - 12:30 **Sháněl:** Industrial perspectives
13:00-14:30 Lunch
14:30 - 15:00 Q&A
15:00-19:00 Practicals

WE 11/9

8:00 - 9:00 Breakfast
9:00 - 10:30 **Basso:** General and Torque magnetometry
10:30-11:00 Coffee
11:00 - 12:30 **Lubk:** Electron holography
13:00-14:30 Lunch
14:30 - 15:00 Q&A
15:00-19:00 Practicals

TH 12/9

8:00 - 9:00 Breakfast
9:00 - 10:30 **Ranno**: Magnetic resonance
10:30-11:00 Coffee
11:00 - 12:30 **Garcia:** Magnetic sensors
13:00-14:30 Lunch
14:30 - 15:00 Q&A
16:00-19:00 Banquet at Brno lake

FR 13/9

8:00 - 9:00 Breakfast
9:00 - 10:30 **Basso:** Indirect techniques
10:30-11:00 Coffee
11:00 - 12:30 **Ranno:** Measuring spin currents
CLOSING
13:00-14:30 Lunch
DEPARTURE

CONT

2
PROGRAM TIMETABLE

6
ABOUT THE ESM, HOST CITY

7
COMMITEES

8
SCHOOL VENUE

9
SITE MAP

10
PRACTICAL INFORMATION

12
WALKING DISTANCE RESTAURANTS, BARS AND PUBS

13
PUBLIC TRANSPORTATION

14
MAPS AND JOURNEY PLANNING

16
LIST OF PARTICIPANTS

E

NTS

21
LIST OF ORGANIZERS

22
LIST OF LECTURERS, INDUSTRY EXPERTS

23
LECTURERS AVAILABILITY

24
LECTURES

68
PRACTICALS

THE EUROPEAN SCHOOL ON MAGNETISM
EXPERIMENTAL TECHNIQUES
BRNO, CZECH REPUBLIC, SEPTEMBER 2-13

The European School on Magnetism (ESM) is a joint action of the European magnetism community and is organized under the auspicies of the European Magnetism Association (EMA). ESM aims at providing young scientists with a thorough up-to-date insight into the fundamentals of magnetism.

As with previous sessions of ESM, the 2019 School is based on a broad range of lectures, with special attention given to experimental techniques. This covers from the fundamental phenomena underlying experimental techniques, to their implementation and data analysis, including hands-on practicals. The School will be an opportunity for young scientists, both experimentalists and theoreticians, to meet and share their expertise.

HOST CITY

Brno is the 2nd largest town in the Czech Republic with over 400,000 inhabitants and the capital of the South Moravian Region.

The city of Brno has a long-year tradition in science and technology, it is connected to prominent scientists and thinkers such as Johann Gregor Mendel, Augustinian friar and the founder of modern genetics, who conducted his pea plant experiments here. For a few decades Brno has been a place of research institutes and companies involved in development and production of electron microscopes. At present it hosts companies such as Thermo Fisher Scientific (FEI), TESCAN, and Delong Instruments, all of them being engaged in the business of electron microscopy and relevant nanotechnology tools and methods. Brno is also known as a student town having more than 80,000 students.

COMMITEES

LOCAL COMMITTEE

M. URBÁNEK (chair), Brno
V. UHLÍŘ (co-chair), Brno
L. FLAJŠMAN, Brno
M. STAŇO, Brno

STEERING COMMITTEE

O. FRUCHART (chair), Grenoble
L. ABELMAN, Saarbrücken
S. BLUNDELL, Oxford
V. FRANCO, Sevilla
L. HEYDERMAN, Villigen & Zürich
O. ISNARD, Grenoble
A. KIRILYUK, Nijmegen
M. PRZYBYLSKI, Kraków

SCIENTIFIC COMMITTEE

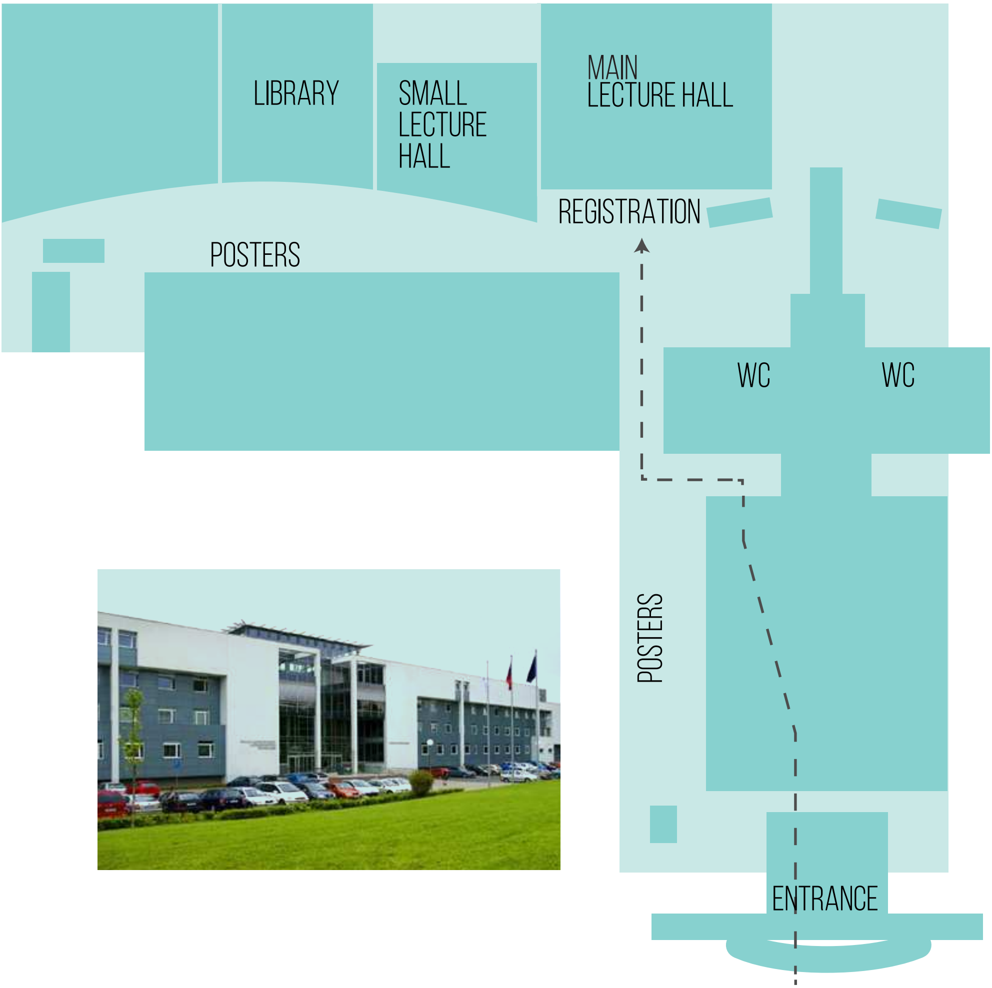
F. ALBERTINI, Parma
A. ASENJO, Madrid
V. CROS, Paris
N. DEMPSEY, Grenoble
S. GONNENWEIN, Dresden
K. SANDEMAN, New-York & London
V. SIMONET, Grenoble
R. STAMPS, Winnipeg
J. STAUNTON, Warwick
S. VALENZUELA, Barcelona
B. Van WAEYENBERGE, Ghent
A. ZORKO, Ljubljana

ORGANIZERS

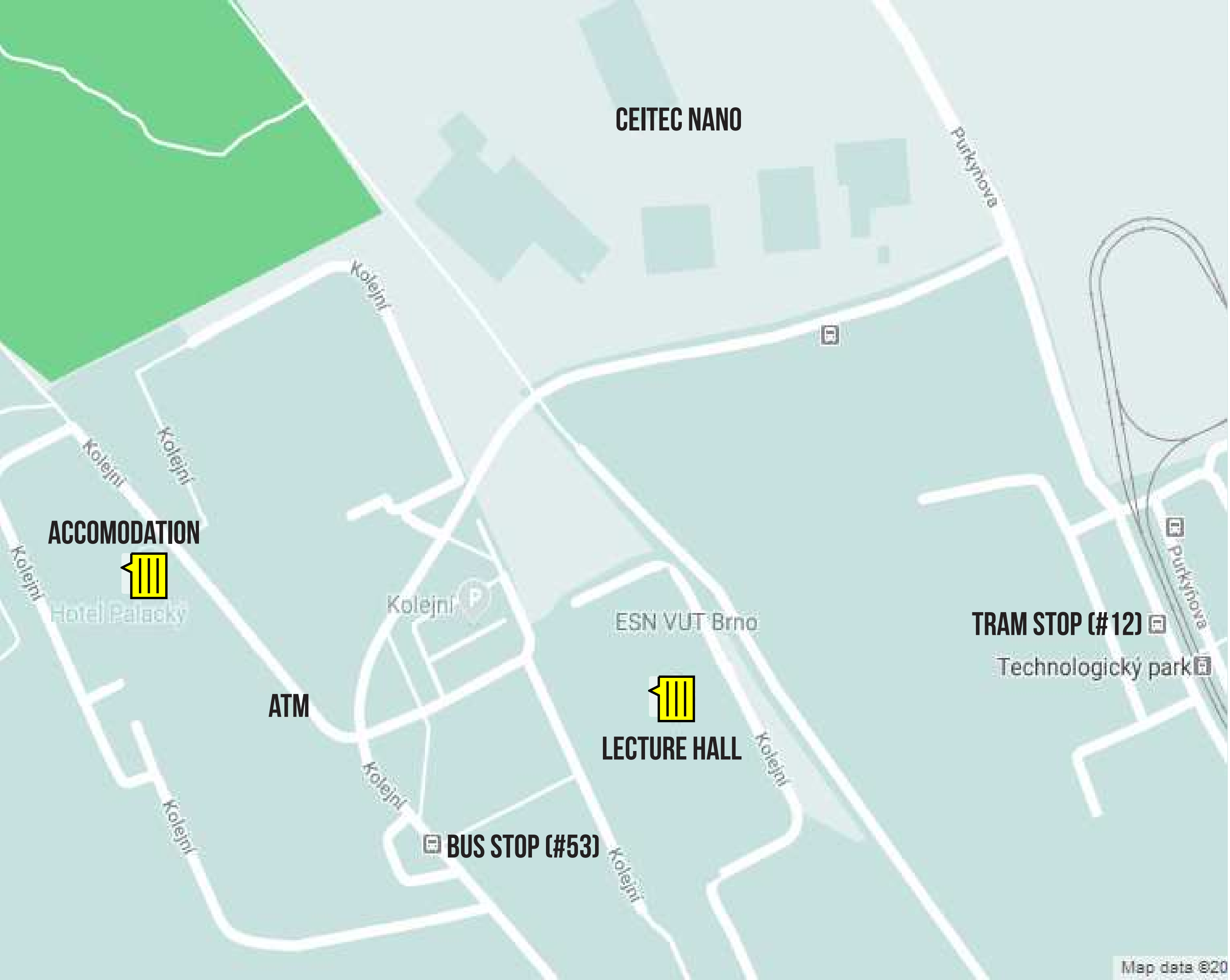
SCHOOL PARTNERS

SCHOOL VENUE

Brno University of Technology, Faculty of Business and Management, Kolejní 2906/4, Brno, Lecture hall e337

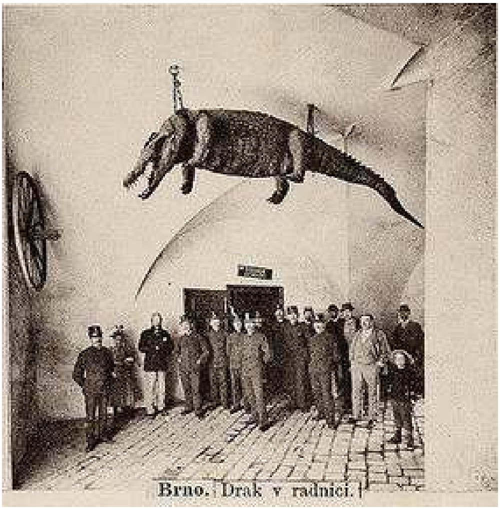


SITE MAP


CEITEC NANO
Purkyňova
Kolejní
Kolejní
Kolejní
ACCOMODATION
Kolejní
Hotel Palacký
Kolejní
ESN VUT Brno
TRAM STOP (#12)
Purkyňova
Technologický park
ATM
LECTURE HALL
Kolejní
Kolejní
Kolejní
BUS STOP (#53)
Kolejní
Map data ©20

PRACTICAL INFORMATION

Why there is a crocodile in the ESM2019 logo? Will there be a practical demonstration of diamagnetic levitation of a crocodile during the ESM practicals?



Actually no, the crocodile is a part of ESM 2019 logo because it is one of the symbols of the City of Brno. A legend says that there was a terrible creature terrorizing the citizens of Brno. The people had never seen such a beast before, so they called it a dragon. They trembled in fear of the dragon until a brave man decided to kill the monster by tricking it into eating a carcass filled with lime. In reality the dragon was a crocodile, the preserved body of which is now displayed at the entrance of the Old Town Hall. Crocodile and dragon motifs are common in Brno. A "krokodýl" (crocodile in the Czech language) is the local stuffed baguette, and the city radio station is known as Radio Krokodýl. Local baseball team is named Draci Brno (en: Dragons Brno) and local rugby club is named RC Dragon Brno, there is also local American football team called Brno Alligators. An Intercity train connecting Brno and Prague is called Brněnský drak (en: Brno dragon).

Although levitating crocodile would be an impressive experiment, unfortunately, as displayed in the ESM 2019 graphics, we do not have a magnet big enough to lift the crocodile... But don't worry, there will be many other exciting lectures and practicals during the school.

CURRENCY

• The currency in the Czech Republic is the Czech Crown (CZK). It is called "koruna" (abbreviated Kč).

• Exchange rate is approximately: 25 CZK for 1 €.

• Coins appear in denominations of 1, 2, 5, 10, 20 and 50. Notes are available in denominations of 100, 200, 500, 1000, 2000 and 5000.

• All major credit and debit cards are widely accepted at shops, hotels, banks and ATM machines. Euros are usually not accepted. Therefore, we recommend having some cash in Czech Crowns.

• You can exchange cash in banks (usually some small fee is applied) or at exchange office (where exchange rates can vary) or use an ATM machine to withdraw – there are a lot of them in the city.

EMERGENCY

Insurance card & ID card or Passport

It is obligatory for all citizens and people present in the Czech Republic to have your insurance cards and ID cards or passports always with you. Please carry it at all times, as you might be checked by members of the Police or the Police Office for Foreigners

Emergency cases

If you are faced with an urgent need for medical attention at a time when doctors' offices are not open, and you are confined to bed, call the first-aid service at +420545538538; a doctor will come to examine you within a very short time. In other cases you should go in person to the emergency service at Ponávka 6, which is open Monday - Friday from 17:00 till 7:00 and non-stop on Saturdays, Sundays and holidays. Emergency dental care is also available at the same address.

Emergency services

Throughout the Czech Republic, there is one set of emergency numbers for use in case of fire, the urgent need for an ambulance, or crime. These are as follows:

Emergency Line 112
Emergency Medical Service 155
Fire Brigade 155
Municipal Police 156
National Police 158

Pharmacies

Most of the medicines available elsewhere can be obtained here, though not in every pharmacy. In case you need some kind of medicine in the evening, at night or over the weekend, when shops are normally closed, there is a non-stop pharmacy located in the city center at Koliště 47.

Police

There are two separate police forces in the Czech Republic, the National Police Force (Policie České republiky) and Municipal Police Force (Městská policie). The National Police deals with such areas as criminal activities, road traffic (accidents, fines and so on), and visas for foreigners. The Municipal Police have limited powers to maintain law and order within the town or city where they work.

Post offices

Most post ofces are only open on weekdays.
The one beside the Main Train Station remains open non-stop, 24 hours a day seven days a week.

WALKING DISTANCE RESTAURANTS, BARS & PUBS

A. KANAS Restaurant, local food
(Su-Th – 11-23:00, Fr-Sa 11:00-00:00)

B. PIVNICE U KOTELNY Restaurant, local food, beer
(Mo-Su – 11:00-23:00)

C. PADTHAI Thai restaurant
(Mo-Su – 11:00-22:00)

D. THE ROSES BEER & COFFEE
Microbreweries and good coffee
(Mo-Fr – 08:00-23:00)

E. NEPAL Indian restaurant
(Mo-Su – 11:00-22:00)

F. BEER LOCAL U BOMBY Beer pub
(Mo-Su – 14:00-23:00)

G. LIQUID BREAD RESTAURANT Restaurant, meat, burgers
(Mo-Sa – 11:00-00:00)

H. FORRUM Whisky and Rum bar
(Mo-Sa – 17:00-01:00)

I. KLUB CESTOVATELU International food
(Mo-Su – 11:00-23:00)

PUBLIC TRANSPORTATION

The best way to travel in Brno is to use public transportation. Every ESM 2019 participant will receive a public transport ticket which is valid for 8 trips 45 min long. Additional tickets will be available at the conference registration desk.

Daily service of public transport in Brno – trams, trolleybuses and buses start at 5:00 (at the weekends at 6:00). Trams are running approximately every 5 minutes from 5:00 to 19:00, at the weekends every 10 minutes, at other times they operate every 10 to 15 minutes.

The best way to get from the ESM venue to the city center is to take the tram 12 from Technologický park and go either to Česká or Hlavní nádraží.

Night bus service starts at 23:00 and continues to 5:00. The night lines are marked with N in front of its number and depart from the Main train station (Hlavní nádraží) at: 23:00 – 23:30 – 0:00 – 0:30 – 1:00 – 1:30 – 2:00 – 3:00 – 4:00 – 4:30 – 5:00. The red departures operate only Fridays and Saturdays. The same tickets as in the day service are valid for the night service.

The best way to get from the city center back to the conference venue at night is to take the night bus N99 at Hlavní nádraží and go either to Kolejní or Technologický park.

MAPS & JOURNEY PLANNING

You can use Google maps for getting around the city, it works just fine. For more detailed maps and journey planning we recommend local services **mapy.cz** and **IDOS** also available for **Android** and **iOS**.

mapy.cz iOS   mapy.cz Android   IDOS iOS   IDOS Android

http://mapy.cz
http://jizdnirady.idnes.cz/brno/spojeni

TAXI

For taxi service we recommend using Liftago taxi via their iOS or Android app. Works as Uber (Uber is not allowed in Brno).

LIFTAGO APP

iOS   Android

BADGES

ORGANIZER

SPEAKER

PARTICIPANT

WIFI

SSID: VUTBR
Login: ESM2019
Password: magnetism

TWITTER

ESM2019_Brno

FACEBOOK

https://www.facebook.com/groups/European-SchoolOnMagnetism/

List of organizers

	**Michal Urbánek** Chair *michal.urbanek@ceitec.vutbr.cz*		**Michal Staňo** *michal.stano@ceitec.vutbr.cz*
	**Vojtěch Uhlíř** Co-Chair *vojtech.uhlir@ceitec.vutbr.cz*		**Lukáš Flajšman** *lukas.flajsman@ceitec.vutbr.cz*

Jana Prušková
CEITEC Events

Kateřina Vlková
CEITEC PR&Marketing

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Igor Turčan
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Marek Vaňatka
CEITEC PhD student

Michal Horký
CEITEC PhD student

Jakub Sadílek
CEITEC Nanofabrication specialist

Meena Dhankhar
CEITEC PhD student

Lucie Motyčková
BUT master's student

Ondřej Wojewoda
BUT master's student

Jakub Holobrádek
BUT master's student

Kristýna Davídková
BUT bachelor's student

Zdeněk Nekula
BUT bachelor's student

LIST OF LECTURERS


OLIVIER
FRUCHART


VIRGINE
SIMONET


LEON
ABELMANN


TOMÁŠ
JUNGWIRTH


ALFREDO GARCIA
ARRIBAS


JAN
LÜNING


VITTORIO
BASSO


AXEL
LUBK


THEO
RASING


RUDOLF
SCHÄFER


LAURENT
RANNO


OLIVIER
ISNARD

INDUSTRY EXPERTS

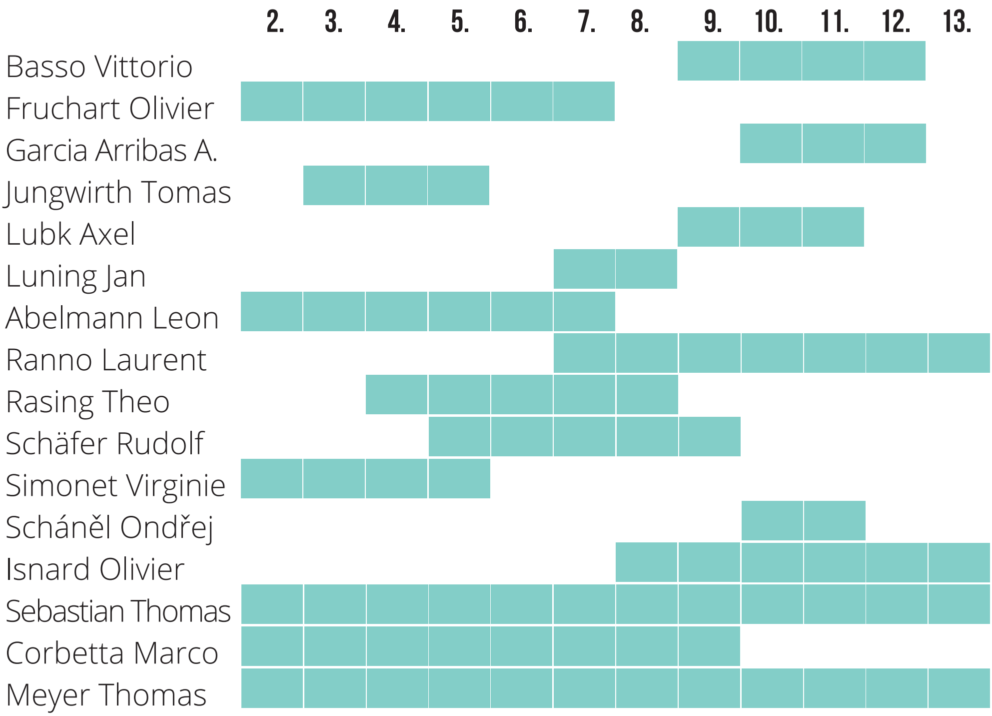

ONDŘEJ
SHÁNĚL


THOMAS
SEBASTIAN


THOMAS
MEYER


MARCO
CORBETTA

LECTURERS AVAILABILITY



LECTURES

FIELDS, MOMENTS, UNITS

Olivier Fruchart
SPINTEC, Grenoble, France
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While expanding knowledge in a field, we tend to consider situations and concepts that are ever more complex. By doing so, our understanding of basic concepts may soften as we do not use them as such, and we consider them as firmly established so that we do not anymore question their significance. Who has never felt unsure when facing induction B versus field H, the discrete versus continuous description of magnetized matter, or conversion from cgs-Gauss to SI units and formulas? In this lecture, I will do my best to shed light on these, turning back to very basic concepts.

Lecture topics:

1. Fields and moments in vacuum
    a. The concepts of electric charge, electric field E, induction field B, the magnetic dipole.
    b. The meaning of Maxwell equations to describe our observations.
    c. Torque and energy of a point dipole
2. Fields and moments in magnetized matter
    a. The description of magnetized matter, and the definition of the magnetic field H.
    b. Amperian and pseudo-charge descriptions of matter
    c. Demagnetizing fields and energies
3. Units and dimensions
    a. What is a physical quantity? What is a unit?
    b. How do S.I. and cgs-Gauss systems differ? How to convert from one system to the other?
    c. Why is the definition of the kilogram intimately linked with magnetism since earlier this year 2019?

Recommended reading:

/1/ W. F. Brown, Micromagnetics, Wiley (1963)
/2/ J. M. D. Coey, Magnetism and Magnetic Materials, Cambridge University Press 2010, Chapter 2 and Appendix B.
/3/ Bureau International des Poids et Mesures, http://www.bipm.org/

MAGNETISM OF ATOMS

Virginie Simonet
Institut Néel, CNRS & Univ. Grenoble Alpes, Grenoble, France
* Virginie.Simonet@neel.cnrs.fr

This lecture is devoted to the building of the isolated magnetic moment at the atomic scale. The magnetic moment is equivalent to a current loop, which allows us to describe quantum mechanically the magnetic moment resulting from one orbiting electron as a combination of orbital and spin angular momenta. The Hund's rules are then recalled that permit to determine the multi-electron magnetic moments of one atom, resulting from Coulomb energy minimization, Pauli exclusion principle and spin-orbit coupling. The spin-orbit interaction and its consequences are detailed. Finally, the temperature anf field-dependent behavior of an assembly of non-interactiong magnetic moments is decribed.

Lecture topics:

1. Formation of a magnetic moment at the atomic scale
2. Hund's rules
3. Spin-orbit interactions in atoms
4. Diamagnetism and paramagnetism of local moments without interactions

Recommended reading:

/1/ J. M. D. Coey, Magnetism and Magnetic Materials, Cambridge University Press, 2010; Chapters 3, 4 and 9.
/2/ S. Blundell, Magnetism in Condensed Matter, Oxford University press (2003); chapters 1, 2.
/3/ L. Ranno, Introduction to magnetism, collection SFN volume 13, 01001, (2014), EDP Sciences, free access

MAGNETIC ORDERING

Leon Abelmann
KIST Europe, Saarbrücken, Germany
*l.abelmann@kist-europe.de

We learned about the diamagnetic response of all atoms to an externally applied field, and paramagnetic response for atoms that have a net magnetic moment. In this lecture we will study what happens if we bring atoms together. Under which conditions do we get a ferro-magnetic material?

Lecture topics:

1. Bound currents
2. Molecular field theory
    a. Heisenberg interaction model
    b. Curie Temperature
3. Exchange
    a. Localized electron model
    b. Delocalized electrons, Band model, super-exchange
    c. Combination, RKKY

In the lectures we will use Peer instruction as a lecture form. This means there will be no presentation by a lecturer. Instead, we expect you to come prepared. At the session, we will discuss the theory guided by concept questions. (This form or education is called Peer instruction https://en.wikipedia.org/wiki/Peer_instruction, it is not meant to relief the lecturer, but based on the idea that you only learn when you are active).

Recommended reading:

/1/ Feynman, Leighton, Sands "The Feynman lecture notes on physics" Chapter 36 (Ferromagnetism), 37 (Magnetic materials). Addison Wesley. Available online: http://www.feynmanlectures.caltech.edu
/2/ Charles Kittel "Introduction to solid state physics" Chapter 11 Diamagnetism and Paramagnetism, Chapter 12 "Ferromagnetism and anti-ferromagnetism" John Wiley.
/3/ Stephen Blundell "Magnetism in condensed matter" Chapter 4, 7

Pre-class Study

The Peer instruction format requires that you study before you attend the lecture. Below we give a list. We realize your backgrounds and preferred text differ. Therefore, we provide options. We use four different textbooks. The Feynman lecture notes on physics is better in insight. Feynman uses more explanation, and is not afraid to indicate where our understanding ends. You will like it if your background is more hands-on. Kittel's solid state physics more precise and condensed. Kittel goes deeper into the theory, and will be more helpful if you continue into solid state problems. Blundell is more modern and very condensed, and rooted in quantum mechanics. You will like it if you studied physics. Chikazumi is from the dark ages, but very complete and pleasant to read. For this session, we would like you to study the following. Depending on your interest and choice you make, it will be 15-25 pages. This will take you about 4 hours.

1. The H-field
Feynman Vol II Chapter 36.1 (Magnetisation currents) and 36.2 (The H-field). (There is no good Kittel chapter for that). 5 pages.

2. Spontaneous magnetism
a) Either continue Feynman: 36.6 (Spontaneous Magnetisation), 37.1 (Understanding Ferromagnetism). 9 pages
b) Or continue with Kittel Chapter 12 "Ferromagnetic Order" (page 323-330 in the 8th edition). 7 pages

3. Direct Exchange.
If you have a background in quantum mechanics, you want to read more about the interaction of two electrons. Either
a) Blundell chapter 4.1/2. 3 pages, or
b) Feynman Vol III Chapter 10.3. 2 pages

4. Super Exchange
Either
a) Chikazumi/Charap chapter 5.1, page 80-81 or Chikazumi/Graham chapter 7.1 page 135-137 2 pages, or
b) Blundell chapter 4.2.3. 2 pages

5. Conduction electrons
If you have a background in quantum mechanics: Blundell 7.1 and 7.2. 5 pages
If not: Kittel Chapter 11 "Paramagnetic Susceptibility of conduction electrons" page 315 in 8th edition. 2 pages
Than read Blundell 4.2.4 (0.5 page)

MAGNETIC INTERACTIONS

Leon Abelmann
KIST Europe, Saarbrücken, Germany
*l.abelmann@kist-europe.de

We learned that some materials spontaneously magnetize below the Curie temperature. In this lecture, we dive deeper into the interaction between the atoms in the crystal.

Lecture topics:

1. Exotic magnetic materials
    a. Anti-ferromagnets
    b. Ferrimagnets
2. Anisotropy
    a. Phenomenological (crystal, magnetostriction, interface)
    b. Pair model
    c. Spin orbit interaction
    d. One ion model

In the lectures we will use Peer instruction as a lecture form. This means there will be no presentation by a lecturer. Instead, we expect you to come prepared. At the session, we will discuss the theory guided by concept questions. (This form or education is called Peer instruction https://en.wikipedia.org/wiki/Peer_instruction, it is not meant to relief the lecturer, but based on the idea that you only learn when you are active).

Recommended reading:

/1/ Feynman, Leighton, Sands "The Feynman lecture notes on physics" Chapter 36 (Ferromagnetism), 37 (Magnetic materials). Addison Wesley. Available online: http://www.feynmanlectures.caltech.edu
/2/ Charles Kittel "Introduction to solid state physics" Chapter 11 Diamagnetism and Paramagnetism, Chapter 12 "Ferromagnetism and anti-ferromagnetism" John Wiley.
/3/ Chikazumi, Charap "Physics of Magnetism" John Wiley, Chapter 3-5 or Chikazumi, Graham "Physics of Ferromagnetism", Oxford Chapter 5-7

Pre-class study

The Peer instruction format requires that you study before you attend the lecture. Below we give a list. We realize your backgrounds and preferred text differ. Therefore, we provide options. We use four different textbooks. The Feynman lecture notes on physics is better in insight. Feynman uses more explanation, and is not afraid to indicate where our understanding ends. You will like it if your background is more hands-on. Kittel's solid state physics more precise and condensed. Kittel goes deeper into the theory, and will be more helpful if you continue into solid state problems. Blundell is more modern and very condensed, and rooted in quantum mechanics. You will like it if you studied physics. Chikazumi is from the dark ages, but very complete and pleasant to read. For this session, we would like you to study the following (we will use flipped classroom, there will be no lecture). Depending on your interest and choice you make, it will be 9-24 pages. This will take you up to 4 hours.

1. Anti-ferro and ferri-magnetism

a) Either Feynman 37.5 (Extraordinary magnetic materials) 3 pages
b) Or get more detail in Kittel Ferrimagnetic order (8th edition page 336-339), Antiferromagnetic order (340-344). 9 pages

2. Anisotropy- phenomological

a) Either: Chikazumi/Graham 12.1 page 249-256 (7 pages) or Chikazumi/Charap chapter 7.1, page 128-132 (3 pages)
c) Or if you lack time: Kittel "Anisotropy Energy", 348-9 (1 page)
d) Or if you really lack time: Blundell 6.7.2 (0.5 page)

3. Anisotropy- pair model/ion model

Than we are stuck with Chikazumi:
a) Chikazumi/Charap 7.2 and 7.3 (12 pages) or
b) Chikazumi/Graham 12.3 (6 pages)

SYMMETRY AND MAGNETO-TRANSPORT PHENOMENA

Tomáš Jungwirth
Institute of Physics, Czech Academy of Sciences and University of Nottingham, United Kingdom
* jungw@fzu.cz

The phase of matter can be characterized by symmetry and for certain effects, symmetry provides the basic condition to occur. In this lecture, we show how the fundamental concepts of symmetry apply to three key functionalities of spintronic memory devices, namely the retention, reading, and writing of magnetic information. Side by side we compare how the principles apply when considering the more conventional ferromagnetic and the richer antiferromagnetic structures.

Magnetism can and often does lower the symmetry of the crystal, depending on the direction of magnetic moments. It implies that reorientation of magnetic moments can change the electronic structure and by this the total energy. This is the origin of the magnetocrystalline anisotropy energy barrier that supports the non-volatile storage in spintronic memories.

Another example is the ferromagnetic order removing the symmetry protection of the spin-up/spin-down degeneracy of electronic bands. As a result, electrons moving in the unequal spin-up and spin-down bands have different resistivities. In ferromagnetic bilayers this leads to different resistance states for parallel and antiparallel alignments of moments in the two layers and the corresponding giant magnetoresistance effects. Different resistivities in spin-up and spin-down transport channels in a ferromagnet can be also used to filter an unpolarised current passing through the ferromagnetic layer by suppressing one spin-component of the electrical current. The resulting spin-polarized current filtered through such a ferromagnetic polarizer can exert a spin transfer torque on the adjacent ferromagnetic layer and switch its magnetic moment.

In time-reversal symmetric paramagnets, a broken space-inversion symmetry leads to the Kramers degeneracy of states with opposite spins and opposite crystal momenta, while the states at a given crystal momentum can be spin split. As a result, the crystal can develop a net spin polarization in a non-equilibrium, current-carrying state. When these relativistic spintronic effects occur at an inversion-asymmetric interface between a paramagnet and a ferromagnet, or inside a magnetic crystal that lacks inversion symmetry, they can induce a spin-orbit torque. The charge to spin conversion efficiency driving the spin-orbit torque can outperform that of the spin-transfer torque and can be equally efficient in ferromagnets and antiferromagnets.

Lecture topics:

1. Charge-spin coupling fundamentals
    a. Coulomb exchange coupling
    b. Relativistic spin-orbit coupling
2. Symmetry and magnetotransport
    a. Magnetic symmetry groups
    b. Anisotropic magnetoresistance
    c. Anomalous Hall effect
    d. Giant magnetiresistance
3. Symmetry and spin-torque
    a. Spin-transfer torque
    b. Spin Hall effect and spin-oribit torque

Recommended reading:

/1/ P. Strange, "Relativistic Quantum Mechanics", Cambridge University Press 1998.
/2/ H. Grimmer, "General relations for transport properties in magnetically ordered crystals", Acta Crystallographica Section A 49, 763–771 (1993).
/3/ J. Sinova et al., "Spin Hall effect", Rev. Mod. Phys. 87, 1213 (2015).

MAGNETIZATION TEXTURES AND PROCESSES

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In this lecture I will introduce the various magnetic states of magnetic materials, and their magnetization processes. These generally occur at a length scale larger than lattice cells, making an atomic and quantum description not practical, and often useless. Magnetization textures is an important aspect of magnetism, as most functional effects of magnetic materials rely on them and their control under some stimuli.

Lecture topics:

1. Magnetic length scales and magnetization states
    a. Magnetic energies in competition
    b. Domains, domain walls, vortices and other spin textures
2. Quasistatic magnetization reversal
    a. Coherent rotation (Stoner-Wohlfarth)
    b. Nucleation-propagation mechanisms
    c. What do we learn from hysteresis loops?
3. Precessional magnetizaiton dynamics
    a. Landau Lifshitz Gilbert equation: precession and relaxation
    b. Spin-torques and other stimuli
    c. Precessional switching
    d. Domain-wall motion
    e.V ortex and skyrmion motion

Recommended reading:

/1/ A. Hubert et R. Schäfer, Magnetic Domains, Springer, 1998.
/2/ R. Skomski, Simple models of magnetism, Oxford, (2008)
/3/ A. P. Guimaraes, Principles of Nanomagnetism, Springer, (2009)

SPINTRONIC MAGNETIC MEMORY DEVICES

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Recording technologies come and go, but magnetic recording is a keeper. The magnetic wire recorder was conceived in 1878, a year after Thomas Edison's invention of the phonograph, and was realized two decades later. It evolved into the tape recorder and hard disk drive. It also led to magnetic core memory, whose run as the main type of random access storage lasted from the mid 1950s to the mid 1970s and whose resistance to radiation damage made it vital for space exploration and the shuttle program. All those devices relied on 19th-century physics: Maxwell's equations.

Nowadays magnetic recording enables an hour of video to be uploaded onto the internet every second of every day, and few of us worry about the physical limits of data storage. In the lecture we will discuss how for today's magnetic recording needs, 20th-century spintronics is essential. It helps readout in a decisive way via giant magnetoresistance and tunneling magnetoresistance spin-dependent phenomena found in structures of alternating ferromagnetic and nonmagnetic conducting or insulating layers. Thanks to those phenomena, read heads are more sensitive and more information can be packed onto hard drives. They also paved the way for a transition from solid state core memories with macroscopic magnetic bits to microelectronic magnetic random access memory (MRAM) chips. For writing, hard drives and first-generation commercial MRAMs still rely on 19th-century physics involving the coupling between an electromagnet used for writing and a permanent magnet that provides storage. Revisiting the means of writing magnetic information on MRAMs had to wait for the 21st century, when researchers began to explore the possibility of using a scalable spintronic approach rather than relying on an external magnetic field. While some variants of this approach have already made it to the second-generation MRAMs, others are a subject of current frontier spintronics research. Latest scientific developments in this area include the utility of relativistic spin-orbit coupling phenomena and the materials basis has expanded from ferromagnets to include also antiferromagnets. As a result, terahertz writing speeds have been experimentally demonstrated and magnetic memories are now also considered as building blocks of artificial neural networks.

Lecture topics:

1. Magnetic recording overview
2. Anisotropic and giant magnetoresistance readout
    a. Hard-drive
    b. Magnetic random access memory
3. Spin-torque writing
    a. Spin-transfer-torque MRAM
    b. Spin-orbit-torque MRAM
4. Advanced spintronics concepts
    a. Ultra-fast devices
    b. Neuromorphics

Recommended reading:

/1/ Chappert, Claude, A. Fert, and Frederic Nguyen Van Dau (2007), "The emergence of spin electronics in data storage." Nature Materials 6 (11), 813–23.
/2/ Kent, Andrew D, and Daniel C Worledge (2015), "A new spin on magnetic memories," Nature Nanotechnology 10 (3), 187–191.
/3/ Sinova, Jairo, and Tomas Jungwirth (2017), "Surprises from the spin Hall effect," Physics Today 70, 38.

MAGNETO-OPTICS

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Magneto-optics describes the influence of magnetic fields or of a spontaneous magnetization on the emission or propagation of light in matter. This presentation will cover the basics of magneto-optics at visible frequencies and its application for domain imaging and magnetometry. For magneto-optics at shorter, X-ray frequencies we refer to the presentation of Jan Lüning.

Lecture topics:

1. Magneto-optical effects
    a. Physical basics
    b. Faraday effect
    c. Kerr effect
    d. Voigt effect
    e. Gradient effect
2. Application of magneto-optical effects
    a. Domain imaging
    b. Magnetometry
3. Recent developments of magnetic domain imaging by wide-field magneto-optical microscopy
    a. Selective sensitivity
    b. Depth sensitive domain imaging
    c. Time-resolved domain imaging
    d. Deconvolution techniques for lateral resolution enhancement
    e. Vector magnetometry and quantitative Kerr microscopy
    f. Magneto-optic indicator films (MOIF)

Recommended reading:

/1/ W. Kuch, R. Schäfer, P. Fischer, and F.U. Hillebrecht, Magnetic Microscopy of Layered Structures (Springer, 2015), chapter 2
/2/ R. Schäfer, Investigation of domains and dynamics of domain walls by the magneto-optical Kerr-effect, in: H. Kronmüller, S. Parkin (Eds.), Handbook of Magnetism and Advanced Magnetic Materials, (John Wiley & Sons 2007)
/3/ J. McCord, Progress in magnetic domain observation by advanced magneto-optical microscopy, J. Phys. D: Appl. Phys. 48 333001 (2015)

NEUTRON SCATTERING

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This lecture will introduce various techniques based on neutron scattering, in particular in the field of magnetism. The properties of the neutron will be recalled, before describing the formalism of the neutron-matter interactions leading to the nuclear and magnetic scattering cross-sections. The diffraction by a magnetic crystal will be presented as a tool to determine magnetic structures. Then I will discuss the use of inelastic neutron scattering to explore magnetic excitations and magnetic hamiltonians. The use of polarized neutrons will be detailed in the context of complex magnetic materials. If time permitted, neutron techniques devoted to nanoscopic objects will be addressed.

Lecture topics:

1. The neutron as a probe of condensed matter
2. Neutron-matter interactions: scattering techniques to probe correlations
3. Diffraction by a crystal: nuclear and magnetic structures.
4. Inelastic neutron scattering: nuclear and magnetic excitations
5. Polarized neutrons: magnetic domains, magnetization density maps, magnetic chirality
6. Reflectometry and small angle scattering

Recommended reading:

/1/ Neutrons and magnetism, collection SFN, volume 13, (2014) EDP Sciences, chapitres 2 to 6, free access
https://www.neutron-sciences.org/articles/sfn/abs/2014/01/contents/contents.html
/2/ G. L. Squires, Thermal neutron scattering, Cambridge University Press (1978).
/3/ S. W. Lovesey, Theory of Neutron scattering from condensed matter, Oxford, Clarendon Press (1984).

TIME-RESOLVED PUMP-PROBE TECHNIQUES

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Magnetization dynamics covers a broad range of timescales, from the slow, microsecond, dynamics of domain wal motion, the sub-nanosecond precessional macroscopic dynamics to the ultrafast femto/picosecond dynamics related to single spin dynamics driven by the strong exchange fields. This lecture will introduce the concepts of how to probe the spin and magnetization dynamics in magnetic materials, in particular the ultrafast regimes, from stroboscobic repetitive dynamics to single-shot magneto-optical imaging.

Lecture topics:

1. Introduction: stochastic/deterministic dynamics
2. Stroboscopic imaging
3. Magneto-optical setups
    a. Faraday/Kerr effects
    b. Magnetic Second Harmonic Generation
    c. XMCD
4. Examples
5. Outlook

Recommended reading:

/1/ Y. Hashimoto, A. R. Khorsand, M. Savoini, B. Koene, D. Bossini, A. Tsukamoto, A. Itoh, Y. Ohtsuka, K. Aoshima, A. V. Kimel, A. Kirilyuk and Th Rasing: Ultrafast time-resolved magneto-optical imaging of all-optical switching in GdFeCo with femtosecond time-resolution and micrometer spatial-resolution. Review of Scientific Instruments, 85 (2014).
/2/ A. I. Kirilyuk, A. V. Kimel and T. Rasing: Ultrafast opto-magnetic excitation of magnetization dynamics. Ieee Transactions on Magnetics, 44 (2008), 1905-1910.
/3/ Alexey V. Kimel, Andrei Kirilyuk and Theo Rasing: Femtosecond opto-magnetism: ultrafast laser manipulation of magnetic materials. Laser & Photonics Reviews, 1 (2007), 275-287.

SCANNING PROBE MICROSCOPY FOR MAGNETISM

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The concept of scanning probe microscopy (SPM) emerged from the invention of the scanning tunneling microscope in 1982, its importance being quickly recognized by the Nobel prize in Physics in 1986. The versatility of SPM comes from the ability to combine the concept of scanning, with many types or probes, sensitie to various physical quantities, including magnetic ones. In this lecture I will review SPM with a magnetic sensitivity.

Lecture topics:

1. Why do we need magnetic microscopies?
2. The early days of scanning probe microscopy: STM and AFM
3. Magnetic force microscopy (MFM)
    a. Conventional MFM
    b. Magnetic resonance force microscopy (MRFM)
4. S pin-polarized STM (sp-STM)
    a. Early days and basics
    b. Current trends
5. Scanning Near-field Optical Microscopy (SNOM)
6. Nitrogen-vacancy center microscopy
7. Scanning devices
    a. Scanning SQUID
    b. Scanning hall probes
    c. Scanning spintronic sensors
8. Overview: assets of the various techniques

Recommended reading:

/1/ H. Hopster, H. P. Oepen, Magnetic microscopy of nanostructures, Springer, (2005).
/2/ Y. Zhu Ed., Modern techniques for characterizing magnetic materials, Springer (2005)
/3/ A. Schwartz et al., Scanning probe techniques: MFM and SP-STM, in : series Handbook of magnetism and advanced magnetic materials, Novel techniques for characterizing and preparing samples (vol.3), H. Kronmüller, S. Parkin Ed. (2007)

ALL-OPTICAL CONTROL OF MAGNETIZATION

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Since the demonstration of ultrafast demagnetization by a 60 fs laser pulse and the subsequent magnetization reversal by a single 40 fs laser pulse, the manipulation of spins by ultra-short laser pulses has become a fundamentally challenging topic with a potentially high impact for future spintronics, data storage and quantum computation. Expansion to hybrid magnetic materials, multilayers, FePt and even magnetic garnets are ongoing efforts to develop all-optical switching (AOS) towards an alternative and energy efficient approach to magnetic recording.

Lecture topics:

1. Time scales and stimuli in magnetism
2. Classification of laser induced effects
    a. Thermal effects
    b. Nonthermal photo-magnetic effects
    c. Nonthermal opto-magnetic effects
3. Experiments
    a. AOS of Ferrimagnets
    b. AOS of Ferromagnets
    c. AOS of Dielectrics
4. Towards applications
    a. All-optical switching at the nanoscale
    b. AOS of recording media
    c. Neuromorphic applications
5. Outlook

Recommended reading:

/1/ A. Kirilyuk, A.V. Kimel, and Th. Rasing, Laser-induced dynamics and reversal in ferrimagnetic alloys. Rep. Prog. Phys. 76, 026501 (2013)
/2/ Andrei Kirilyuk, Alexey V. Kimel and Theo Rasing: Ultrafast optical manipulation of magnetic order. Reviews of Modern Physics, 82 (2010), 2731-2784. Review of Modern Physics 88, 039904 (2016)

X-RAY TECHNIQUES: SYNCHROTRON, FEL, HHG

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In this lecture I will introduce how femtosecond pulsed X-ray sources have been employed to study ultrafast magnetization dynamics. Relevant experimental results and the respectively employed techniques will be introduced and novel experimental schemes, currently implemented or envisioned, will be discussed.

Lecture topics:

1. Introduction
    a. X-ray related interactions with the sample
    b. X-ray optics
2. Synchrotron based techniques
    a. Types of X-ray sources
    b. XMCD
        i. Element specificity
        ii. Sum rules
        iii. MTXM
        iv. X-PEEM
    c. X-ray diffraction
    d. Linear magnetic dichroism
3. Free electron lasers
    a. Recent development
4. High-harmonic-generation X-ray sources
    a. Principle
    b. State of the art

Recommended reading:

/1/ E. Beaurepaire et al., Phys. Rev. Lett. 76, 4250 (1996).
/2/ C. Stamm et al., Nature Materials 6, 740 (2007).
/3/ B. Vodungbo et al., Nature Communications 3, 999 (2012).

X-RAY HOLOGRAPHY, TOMOGRAPHY

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The lecture will cover basic of X-ray holography and tomography techniques as well as provide experimental examples.

Lecture topics:

1. X-ray holography
   a. In-line
   b. Off-axis
   c. Fourier transform holography
2. Experimental setups
3. Technique characteristics
   a. Magnetic sensitivity (XMCD, polarized X-rays)
   b. Elements sensitivity (resonant scattering)
   c. Resolution
   d. Probed volume
4. Tomography
5. Examples of measurements
6. X-ray ptychography (+tomography)

Recommended reading:

/1/ Pfau B., Eisebitt S. X-Ray Holography. In: Jaeschke E., Khan S., Schneider J., Hastings J. (eds) Synchrotron Light Sources and Free-Electron Lasers. Springer 2016.

ELECTRON MICROSCOPY AND SPECTROSCOPY

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Electron microscopy and spectroscopy techniques have been for long developed to provide researchers with ultimate spatial resolution characterization as the characteristic dimensions of studied objects are continuously shrinking. When applied to magnetic materials, electron-based approaches do not only offer the ultimate spatial probe for magnetic fields via Lorentz force and Aharonov-Bohm phase, but also the possibility to study their crystallographic structure, chemical composition and dynamic magnetization effects in time domain (Ultrafast TEM) or frequency domain (electron energy loss spectroscopy - EELS). We will give an introduction into pertinent techniques and discuss their basic principles.

Lecture topics:

1. Electron microscopies for magnetic materials
    - a. TEM based magnetic imaging techniques
        - i. Lorentz TEM
        - ii. Electron holography
        - iii. Differential Phase Contrast
    - b. SEM based magnetic imaging techniques
    - c. Comparison of the methods – when to use what?
2. Electron spectroscopies and time-resolved approaches for magnetic materials
    - a. EELS and Energy-Loss-Chiral Dichroism (EMCD)
    - b. Ultrafast TEM

Recommended reading:

/1/ M. D. Graef, Magnetic imaging and its applications to materials, Academic press (2001).
/2/ P. Schattschneider, Linear and Chiral Dichroism in the Electron Microscope, Taylor and Francis (2012).

GENERAL MAGNETOMETRY

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We discuss the basics to understand the characterization of the hysteresis properties of ferromagnetic materials. We will address: the magnetization and the magnetic field in bulk materials; the methods to generate and to accurately measure the magnetic field and the methods of magnetic moment measurement.

Lecture topics:

1. Introduction to magnetic measurements
    a. Quantities: magnetic induction and flux, magnetization and magnetic moment, magnetic field
    b. Magnetostatics and demagnetizing effects
    c. The M versus H hysteresis loop of ferromagnetic materials

2. Measurement of the magnetic field
    a. Metrological aspects
    b. Generation of magnetic fields
    c. Measurement: from high sensitivity to high spatial resolution

3. Measurement of M vs H of magnetic materials
    a. Characterization of soft and hard magnetic materials
    b. Measurement of the magnetic moment (VSM, AGFM, etc)
    c. Magnetic torque measurements

Recommended reading:

/1/ F. Fiorillo, Measurement and characterization of magnetic materials. Elsevier, Amsterdam (2004).
/2/ Magnetism: Materials and Applications, Volume 2 (E. du Trémolet de Lacheisserie, D. Gignoux and M. Schlenker, eds.), Springer, Boston (2005)
/3/ High Sensitivity Magnetometers (Grosz, Haji-Sheikh, and Mukhopad-hyayeds. eds.) Springer (2017).
/4/ S. Tumanski, Handbook of Magnetic Measurement, CRC Press (2011)

ELECTRON HOLOGRAPHY AND TOMOGRAPHY

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Magnetic fields impose a phase shift on beam electrons traversing a magnetic material. Phase contrast techniques and holography in the TEM can reveal that so-called Aharonov-Bohm phase with nanometer resolution, providing insight into the magnetism of the material. This lecture will introduce electron holography from fundamentals to applications. We discuss the most prominent holographic setups and their pertinent reconstruction principles – namely focal series holography, transport of intensity holography and off-axis holography. Finally, we combine holography and tomography to reconstruct the 3D distribution of electric and magnetic fields and show which magnetic properties can be derived from these.

Lecture topics:

1. Fundamentals of electron scattering
    a. Axial scattering
    b. Magnetic and electric Ehrenberg–Siday–Aharonov–Bohm effect
2. Fundamentals of Electron Holography and Tomography
    a. Holographic Principle (interference, reconstruction)
    b. Holographic Setups (inline, off-axis) and instrumental require ments (coherence, focus calibration, biprism)
    c. Separation of electrostatic and magnetic contributions
    d. Tomographic reconstruction of 3D electric potential and mag netic induction vector field from tilt series of projections
3. Magnetic fields and textures in solids
    a. Magnetization, Magnetic induction, Magnetic field
    b. Magnetostatics
    c. Micromagnetics
    d. Vortices, Skyrmions and more

Recommended reading:

/1/ H Lichte et al., Electron holography for fields in solids: Problems and progress, Ultramicroscopy 134, 126-134.
/2/ Introduction to Electron Holography (Ed. E. Völkl, L.F. Allard, D.C. Joy,), Plenum Press (1999).

MAGNETIC RESONANCE

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This lecture will introduce the concept of electron magnetic resonance. Placing electrons in an applied field induces a Zeeman splitting giving rise to electron spin resonance (ESR). In ferromagnetic materials, exchange interaction, magnetisation and anisotropies also play a role and ferromagnetic resonance (FMR) is an extension of ESR. Links between resonance and time-domain magnetisation dynamics (precession, reversal) will be discussed as well as applying similar concepts to nuclear spins (NMR).

Lecture topics:

1. Basic concepts
    a. Electron properties
    b. Spin dynamics
    c. Magnetic Timescales
2. Electron spin resonance
    a. Theory
    b. Experimental Set-ups and Examples
3. Ferromagnetic resonance
    a. From ESR to FMR
    b. Uniform and Non Uniform Modes
    c. Set ups and examples (cavity and broadband)
4. Nuclear magnetic resonance

Recommended reading :

/1/ J. M. D. Coey, Magnetism and Magnetic Materials, Cambridge University Press (2010).
/2/ S. Blundell, Magnetism in Condensed Matter, Oxford University Press (2001).
/3/ C. Kittel, Introduction to Solid State Physics, Wiley (2005).

MAGNETIC SENSORS

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In this lecture, we will revise the main concepts related to the fundamentals and operation principle of magnetic sensors, devices generally associated with the laws and effects of electromagnetic fields and magnetic materials. In this way, devices based on the laws of magnetic induction and sensors based on materials whose properties change under the effect of a magnetic field will be described. Examples of actual devices will illustrate the description of the different operation principles.

Lecture topics:

1. Introduction and basic principles
    a. Overview of applications of magnetic sensors
    b. Magnetic induction
    c. Magnetic materials for sensors
2. Sensing principles and examples
    a. Inductive sensors (LVDT, fluxgate)
    b. SQUID sensors (magnetometers)
    c. Hall effect sensors (magnetic compass, encoders)
    d. Magnetoresistance sensors: AMR, GMR, TMR, GMI
    e. Magnetoelastic sensors (anti shoplifting labels)

Recommended reading:

/1/ C. W. de Silva, Sensor systems: fundamentals and applications (CRC press, 2017). ISBN: 9781498716246
/2/ J. R. Brauer, Magnetic actuators and sensors (Wiley & Sons, 2006). ISBN: 0-471-73169-2
/3/ Magnetic sensors and magnetometers, Ed. Pavel Ripka (Artech House, 2001)-ISBN: 1-58053-057-5

INDIRECT TECHNIQUES

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Reciprocal relation of thermodynamics permits one to relate different extensive quantities like volume, entropy dipole moment and magnetic moment among each other. We will review some of these effects in ferromagnetic materials by underlying the main experimental techniques together with their possibilities and their limitations. Similarly we will review magnetoresistance effects used as a probe of the magnetic state of ferromagnetic metals.

Lecture topics:

1. Volume, strains, and magnetostriction effects
   a. Magnetostriction
   b. Measurement of strain and volume changes

2. Heat, entropy and magnetocaloric effects
   a. Magnetocaloric effect
   b. Measurement of specific heat and entropy change

3. Transport properties and magnetization
   a. The magnetoresistence effects
   b. The (anomalous) Hall effects of ferromagnets

Recommended reading:

/1/ R. O'Handley, Modern magnetic materials: principles and applications, John Wiley & Sons, New York (2000).
/2/ J. M. D. Coey, Magnetism and Magnetic Materials, Cambridge University Press (2010).

MEASURING SPIN CURRENTS

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This lecture will deal with electronic spin currents, how to generate them, how to detect them and the different physical effects that arise when spin currents without charge currents are manipulated.

Lecture topics:

1. Reminders
    a. Charge currents and electronics
    b. Charge+Spin currents and Spin Electronics
    c. Pure Spin currents
2. Spin current generation
    a. Electrical (spin injection, spin-orbit)
    b. Electromagnetic (spin pumping)
    c. Thermal
3. Spin current detection
    a. Electric detections (Spin Hall - SpinTorques)
    b. Electromagnetic/Optical detections
4. Devices
    a. 2-3-4 terminal devices
    b. multilayers and spin valves

Recommended reading :

/1/ A.P. Guimaraes, Principles of Nanomagnetism, Springer 2017

PRACTICALS

UNITS

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This hands-on practical on units of physical quantities follows and extands the lecture "Fields, Moments, Units". In this tutorial we derive the dimensions for physical quantities of use in magnetism, and their conversions between cgs-Gauss and SI.

Topics:

1. Notations
   a. Physical quantity, dimension
   b. 4 fundamental dimensions, MKSA system
2. Finding dimensions of physical quantities based on physical laws
   a. Mechanics
   b. Magnetism
3. Conversions (SI – cgs)
   a. Force, energy
   b. Magnetic induction, flux, magnetic moment, magnetization
   c. Vacuum permeability

d. Magnetic susceptibility, demagnetizing coefficients

Recommended reading:

/1/ Bureau International des Poids et Mesures: http://www.bipm.org/
siunitx LaTeX package: https://ctan.org/pkg/siunitx
/2/ F. Cardarelli, Encyclopedia of Scientific Units, weights and measures, Springer, London, 2003.

EXPERIMENTAL MAGNETISM OFF THE LAB

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3 special experimental practicals will be organized. Each of them will last 2h and gather 18 students.

The idea is to split the room in 6 groups and to address a magnetic problem for 20'. 6 problems will then circulate during each session. Each problem is based on a simple experiment (which can be rather easily transported). The idea is to perform the experiment and then to propose an explanation, qualitative at first, and then as quantitative as possible (time permitting). Each problem will illustrate a magnetic concept.

The planned list of experiments is the following:

- Levitation (at 300K)
- Magnetic Gun (Energy conservation)
- Fridge Magnets (Stray fields)
- Magnetic Brake
- Magnetic Sensing / Fluxgate
- Magnetisation (Temperature dependence)

CONTROLLING LABORATORY EXPERIMENTS IN LABVIEW

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Local responsible person: Lukáš Flajšman**
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In this practical session we introduce the basic concepts of the graphical programming language LabVIEW (LV) from National Instruments. LV aims at the rapid development of software for control and measurement technology by scientists and engineers without a strong background in programming. This session is dedicated to students who are new to LV or are on a beginner level. Particular emphasize will be the development of software with graphical user interface for the automation of laboratory devices.

The first part of the session will cover the following concepts theoretically and practically:
1. Introduction to LV development environment
2. Data types and their graphical representation in user interfaces
3. Control structures: loops, if/case structures, user events, ...
4. Multithreading and data communication via queues and notifiers
5. Hardware I/O and interfaces: VISA, DLLs, ...

In the second part of the session we will use these concepts for the
1. Control of real laboratory devices with different hardware interfaces
2. Data acquisition with laboratory devices and data visualization
3. Data storage in different formats
4. Cross-device measurements with your modules

The third part of the session is interactive and reserved for your questions as well as discussions and programming examples of (advanced) topics of your choice.

Recommended reading *(not required for participation in this practical session):*

/1/ LabVIEW by National Instruments
/2/ Introduction to LabVIEW by National Instruments

MAGNETO OPTICAL KERR MICORSCOPY

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In this practical session we will investigate the static magnetization landscapes by utilizing the wide-field magneto optical Kerr microscope. The Kerr microscopy has rendered itself as one of the major investigation tools for magnetic thin films and micro/nanostructures. Stimulated by the advances of low noise cameras and high real-time data processing possibilities, it allows to visualize magnetization processes with high spatial resolution with vector capabilities.

In the introductory part of the practicals we will introduce the concept of magneto-optical Kerr effect and how it can be utilized in magnetic microscopy. We will introduce also the concept of vecotr Kerr magnetometry.

In the experimental part we will
1. Introduce the setup for wide-field Kerr micorscopy
2. See, how static domain images can be easily visualized by background substraction – see how the contrast can be optimized for best SN ratio.
3. Measure local hysteresis loops on magnetic microstructures.
4. Explore the vector capabilities of the setup.

Recommended reading:
/1/ H. Hopster, H. P. Oepen, Magnetic Microscopy of Nanostructures, Springer, Berlin, Heidelberg (2005) ISBN 978-3-540-40186-5
/2/ A. Hubert, R. Schäfer, Magnetic domains, Springer, Berlin, Heidelberg (1998) ISBN 978-3-540-64108-7

BRILLOUIN LIGHT SCATTERING

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In this practical session we will investigate spin-wave excitations in ferromagnetic microstructures using Brillouin light scattering (BLS) microscopy which is a well established spectroscopic tool for the characterization of spin waves. BLS is the inelastic scattering of light from spin waves and has several benefits: the ability to measure thermal spin waves, to map the spin-wave intensity with high spatial resolution, the possibility to simultaneously detect the spin-wave frequency and wave vector, and the possibility to monitor the spin-wave intensity with temporal resolution.

In the introductory part of the session we will introduce the concept of inelastic scattering of photons from spin waves. In addition, we will discuss the dispersion relation of spin waves in magnetic thin films and introduce the external excitation of spin waves via microwave currents in antennas embedded in magnetic microstructures.

In the experimental part we will

1. introduce the setup for BLS microscopy.
2. explore thermal spin-wave spectra and identify individual resonances and their dependence on the external magnetic field.
3. contact the sample with microwave probes and excite spin waves via antenna structures on the sample.
4. explore propagation characteristics - like propagation length and the occurrence of different width modes - in a spin-wave waveguide.
5. explore the intrinsic nonlinearity of the spin-wave system.

Recommended reading:

/1/ S. O. Demokritov, B. Hillebrands, A. N. Slavin, Brillouin light scattering studies of confined spin waves: linear and nonlinear confnement, Physics Reports 348 (2001)
/2/ T. Sebastian, K. Schultheiss, B. Obry, B. Hillebrands, H. Schultheiss, Micro-focused Brillouin light scattering: imaging spin waves at the nanoscale, Frontiers in Physics 3 (2015)

MICRO AND NANOLITOGRAPHY

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In this practical session we will outline the basics of microfabrication of magnetic devices and structures. The students will go through multistep lithography process and will prepare a set of samples suitable for domain observation in Kerr microscopy as well as for magnetotransport measurements.

Outline:

The first 45 minutes will be devoted to an introductory part outside of the cleanroom and the rest of the practicals will take students to the cleanroom where they will go through the following tasks:

1. We will start with prefabricated chips on 2” wafer with contact pads and alignment marks
2. Spincoating of photoresist layer
3. Photolithography exposure of magnetic structures + development
4. Magnetic layer(s) deposition
5. Lift-off in organic solvents
6. Spincoating of photoresist layer
7. Photolithography exposure of electrical contacts + development
8. Lift-off in organic solvents
9. Final cleaning
10. Packaging

All students who sucessfully finnish this practical will take their produced samples for further characterization (or as a remembrance item).

Recommended reading:

/1/ P. M. Martin (ed.), Handbook of deposition technologies for films and coatings: science, applications and technology. Third edition., Amsterdam: Elsevier, 2010. ISBN 978-0-8155-2031-3.
/2/ S. Franssila, Introduction to microfabrication. 2nd ed., John Wiley, 2010. ISBN 978-0-470-74983-8.

MAGNETIC FORCE MICROSCOPY

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In this practical we will conduct a magnetic force microscopy imaging on different samples at various conditions (pressure, field, temperature). In the 4-hour-practical, two groups of students (3 per group, 6 in total) will have a chance to experience 2 different microscopes: the Bruker Dimension Icon and the NanoScan VLS-80.

Tentative dates: Tuesday 3rd, Wednesday 4th, and Thursday 6th September.

Practical topics:

1. Atomic and magnetic force microscopy
    a. Basics
    b. Probes, exercise: mounting of probes
2. Bruker Dimension Icon microscope
    a. Basic demonstration on a (older) hard-disk drive (HDD), or NiFe microstructures (patterned thin film)
    b. MFM vs temperature on FeRh (metamagnet), or GdCo (fer rimagnet)
3. NanoScan VLS-80 microscope (measurement under high vacuum)
    a. (Electrical) contact potential difference measurement + com pensation
    b. In-field measurement on NiFe structures
    c. (if problems with field): High-resolution measurement on HDD / bit patterned media

Further/ Recommended reading:

/1/ P. Eaton & P. West, Atomic Force Microscopy, Oxford, 2010.
/2/ H. Hopster & H.P. Oepen (Eds.), Magnetic microscopy of nanostructures, Springer, 2005; Chapters 9-13.
/3/ Kazakova et al., Frontiers of magnetic force microscopy, JAP 125, 060901, 2019.

SCANNING ELECTRON MICROSCOPY WITH POLARIZATION ANALYSIS (SEMPA/SPIN-SEM)

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SEMPA, an ultra-high vacuum based technique, allows for an imaging of magnetic surfaces thanks to a detection of spin (spin-polarization) of secondary electrons emitted from a (ferro)magnet. It enables a simultaneous mapping of magnetization in two orthogonal directions (two in-plane, or one in-plane + out-of-plane components). This surface-sensitive microscopy is suitable for ultrathin samples (even few atomic layers). The spatial resolution can be even below 10 nm, but typically it is ≥20nm (trade-off between signal/acquisition time and resolution).
In this practical we will have a look on basics and instrumentation of the SEMPA. After a short introduction, we will check the cleanliness of our sample (surface) with a surface sensitive chemical analysis and do magnetic imaging on Fe microstructures.

1. SEMPA
    a. Basics (what it measures, extreme surface sensitivity, ...)
    b. Requirements (UHV, clean sample surface & detector crystal)
    c. Sample (surface) preparation (sputtering, heating, decoration)
    d. Instrument description (brief)
2. Auger spectroscopy: Is my surface clean enough?
    a. Auger effect and basics
    b. Auger spectra measurement and identification
3. Magnetic imaging
    a. Setting up, crystal (detector) cleaning
    b. Imaging of Fe microstructures (patterned thin film).

Further/Recommended reading:

/1/ H. Hopster & H.P. Oepen (Eds.), Magnetic microscopy of nanostructures, Springer, 2005; Chapter 7.
/2/ K. Koike, Spin-polarized scanning electron microscopy, Microscopy 62(1), 177–191, 2013.
/3/ J. Unguris, 6. Scanning electron microscopy with polarization analysis (SEMPA) and its applications. In Experimental methods in the physical sciences (Vol. 36, pp. 167-193, XV-XVI), Academic Press, 2001.

VIBRATING SAMPLE MAGNETOMETRY

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In this practical session we will use vibrating sample magnetometry (VSM) for magnetic characterization of ferrimagnetic and metamagnetic materials. VSM gives the possibility to measure magnetic hysteresis as a function of magnetic field or temperature. The advantage is that it measures directly the magnetic moment of the sample, from which the value of magnetization can be determined.

In the introductory part of the session we will discuss the working principle of the instrument and expected magnetic characteristics of the samples that we are going to analyze.

In the experimental part we will

1. Measure magnetic hysteresis of CoTb or CoGd thin films across the magnetization compensation point.
2. Measure the thermal hysteresis of magnetization in a FeRh thin film across the metamagnetic phase transition.

Recommended reading:

/1/ S. Foner, The vibrating sample magnetometer: Experiences of a volunteer, J. Appl. Phys. 79, 4740 (1996).
/2/ S. Foner, Versatile and Sensitive Vibrating-Sample Magnetometer, Rev. Sci. Instrum. 30 (7), 548–557 (1959).
/3/ https://www.qdusa.com/products/versalab.html

LORENTZ TRANSMISSION ELECTRON MICROSCOPY

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Lorentz microscopy has been used extensively for the past 40 years to study magnetic domain structure and magnetization reversal mechanisms in magnetic thin films and elements. It uses a transmission electron microscope to penetrate a thin sample where its magnetization can cause deflection of the electrons creating a magnetic contribution to the signal captured on camera/detector. Normal operation of every modern TEM instrument includes an objective lens which immerses the sample space with very high magnetic field (approx. 2T) which doesn't allow for observation of remanence magnetization states. For this reason, the objective lens is typically turned off during the magnetic imaging sacrificing a lot of spatial resolution. On the other hand, the objective lens can be slightly excited to introduce controlled magnetic field influencing the sample.

In the introductory part of the session we will discuss the working principle of the TEM microscope and its alignments needed for the Lorentz microscopy using Fresnel (defocused) imaging on camera and Differencial Phase Contrast (DPC) imaging on a STEM detector.

In the experimental part we will examine a sample consisting patterned NiFe layer on a 30nm SiN membrane showing several typical domain structures (Landau patterns, vortices, multidomains) using:

1. Fresnel imaging mode on camera
2. DPC using STEM mode imaging of a segmented detector
3. Simulation of Fresnel mode images using micromagnetic simulations and their comparison to images captured on the microscope

Recommended reading:

/1/ H. Hopster, H. P. Oepen, Magnetic Microscopy of Nanostructures. NanoScience and Technology, Springer (2005). doi:10.1007/b137837
/2/ Zweck, J. & Uhlig, T. Lorentz Microscopy of Thin-film Systems. Handbook of Magnetism and Advanced Magnetic Materials (2007).
/3/ Petford-Long, A. & Chapman, J. Lorentz Microscopy. Magnetic Microscopy of Nanostructures NanoScience and Technology 67–86 (2005)

FERROMAGNETIC RESONANCE VNA-FMR

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Ferromagnetic resonance (FMR) is a well-established experimental technique for magnetic sample characterization. FMR linewidth analysis in particular has considerably regained interest these days, due to the relation between the resonance peak width and the damping of magnetization motion. The standard FMR experiment uses fixed frequency by the employed microwave cavity while sweeping magnetic field. On the other hand, Vector network analyzer-FMR (VNA-FMR) can sweep frequency and measure reflected/transmitted power while the external magnet can sweep the magnetic field providing 2D scans over both quantities providing much bigger set of data. The sample is excited by passing the RF signals through a coplanar waveguide (CPW) over which the sample is positioned.

In the introductory part of the session we will discuss the working principle of the VNA in relation to the CPW exciting the samples, the signals measured by VNA and their relation to FMR.

In the experimental part we will

1. Learn how to manipulate and position microwave probes
2. Perform a calibration of vector network analyzer (VNA)
3. Measure ferromagnetic resonance of thin layers of magnetic materials
4. Evaluate magnetic parameters of samples by fitting the experimental data.

Recommended reading:

/1/ Kalarickal, S. S. et al. Ferromagnetic resonance linewidth in metallic thin films: Comparison of measurement methods. Journal of Applied Physics 99, 093909 (2006).
/2/ Kalarickal, S. S. et al. Ferromagnetic resonance linewidth in metallic thin films: Comparison of measurement methods. Journal of Applied Physics 99, 093909 (2006).
/3/ M. Heibel, Fundamentals of Vector Network Analysis, Rohde&Schwarz (2008).