# Symposium Attosecond and coherent spins: New frontiers (SYAS)

jointly organized by
the Magnetism Division (MA),
the Thin Films Division (DS),
the Semiconductor Physics Division (HL),
the Surface Science Division (O), and
the Low Temperature Physics Division (TT)

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Ultrafast magnetism, attosecond lasers and methods using x-ray pulses to explore structural dynamics are reaching new limits. This session is dedicated to new developments and recent major recent milestones, from hard x-ray bunches to attosecond pulses, breaking new frontiers and time records, towards the observation to study coherent spin processes. This phenomena is originating from coherent charge transfer, driven by a few cycle laser pulse, and is relevant for all materials and interfaces, from semiconductors, metals to molecules. Examples for these systems will be demonstrated.

## Overview of Invited Talks and Sessions

(Lecture hall HSZ 02)

### Invited Talks

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| SYAS 1.1 | Mon | 15:00–15:30 | HSZ 02 | **Ultrafast Coherent Spin-Lattice Interactions in Ferromagnets** — •Steven L. Johnson |
| SYAS 1.2 | Mon | 15:30–16:00 | HSZ 02 | **Ab-initio treatment of ultrafast spin-dynamics** — •Sangeeta Sharma, J. K. Dewhurst |
| SYAS 1.3 | Mon | 16:00–16:30 | HSZ 02 | **Light-wave driven Spin Dynamics** — •Martin Schultze, Sangeeta Sharma, Markus Münzenberg |
| SYAS 1.4 | Mon | 16:45–17:15 | HSZ 02 | **All-coherent subcycle switching of spins by THz near fields** — •Christoph Lange |
| SYAS 1.5 | Mon | 17:15–17:45 | HSZ 02 | **Ultrafast optically-induced spin transfer in ferromagnetic alloys** — •Stefan Mathias |

### Sessions

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| SYAS 1.1–1.5 | Mon | 15:00–17:45 | HSZ 02 | **Attosecond and Coherent Spins: New Frontiers** |

# SYAS 1: Attosecond and Coherent Spins: New Frontiers

Time: Monday 15:00–17:45 Location: HSZ 02

**Invited Talk** SYAS 1.1 Mon 15:00 HSZ 02

**Ultrafast Coherent Spin-Lattice Interactions in Ferromagnets** — •Steven L. Johnson — Institute for Quantum Electronic, Eidgenossische Technische Hochschule, Zürich, Swiitzerland — SwissFEL, Paul Scherrer Institut, Villigen, Switzerland

The interaction of spins in a ferromagnet with the underlying lattice during the process of ultrafast demagentization has for some time been shrouded in mystery, and is intimately connected to the fundamental question of exactly how angular momentum is conserved in such processes. The original Einstein de Haas experiment of the early 20th century showed dramatically that the angular momentum of the electron spins responsible for ferromagnetism is the same angular momentum that we know well from classical mechanics. In this talk I explore how the Einstein de Haas effect can manifest in the time domain on ultrafast time scales in response to ultrafast demagnetization of a 3d ferromagnet. In a thin film geometry, the transfer of angular momentum to the lattice is accomplished by a transient mechanical torque that launches a small but measurable transverse displacement wave into the film. I also describe an experiment using ultrafast x-ray diffraction performed at the LCLS free electron laser that observed these dynamics. Based on this we make a first estimate of the magnitude and time scale of angular momentum transfer to the lattice in the first few hundred femtoseconds after ultrafast demagnetization. I also discuss future directions in this research to further investigate the underlying mechanisms.

**Invited Talk** SYAS 1.2 Mon 15:30 HSZ 02

**Ab-initio treatment of ultrafast spin-dynamics** — •Sangeeta Sharma[1] and J. K. Dewhurst[2] — [1]Max-Born Institute for Nonlinear Optics and Short Pulse Spectroscopy, Max-Born-Strasse 2A, 12489 Berlin, Germany — [2]Max planck Inst. Halle, Weinberg 2, 06120 Halle

I will talk about all-optical switching of long-range magnetic order. The type of coupling between the constituent atoms of a magnetic solid, usually ferromagnetic (FM) or anti-ferromagnetic (AFM), is a fundamental property of any magnetic material. This coupling is governed by the exchange interaction, for which the time scale of a typical magnetic material is of the order of a few 100s of femtoseconds. In our work, using time-dependent density functional theory (TDDFT), we demonstrate that a rich control over magnetization at sub-exchange time scales (of the order of few tens of femtoseconds) is possible[1,2,3,4]. This even includes changing the magnetic order from AFM to FM[5]. By investigating a wide range of multi-sublattice magnetic materials we are able to formulate three simple rules that predict the qualitative dynamics of magnetization for ferromagnetic, anti-ferromagnetic, and ferri-magnetic materials on sub-exchange time scales.

[1] Shokeen et al. Phys. Rev. Lett. 119, 107203 (2017) [2] Elliott et al. Scientific Reports 6, 38911 (2016) [3] Chen et al. Phys. Rev. Lett. 122, 067202 (2019) [4] Siegrist et al. Nature 571, 240 (2019) [5] Dewhurst et al. Nano Lett. 18, 1842, (2018)

**Invited Talk** SYAS 1.3 Mon 16:00 HSZ 02

**Light-wave driven Spin Dynamics** — •Martin Schultze[1], Sangeeta Sharma[2], and Markus Münzenberg[3] — [1]TU Graz, Österreich — [2]MBI Berlin — [3]U Greifswald

In electronics, functionality is achieved by switching between electronic states of matter by applying external electric or magnetic fields. Strong couplings in-between charge carriers and to the crystal lattice conspire to randomize energies and momenta extremely fast and efficiently, leaving no room for any sort of coherence.

However, the prospects of coherent control protocols as demonstrated in isolated atomic systems are alluring and contemporary ultrafast laser sources might be a new ingredient to overcome this entrapment. This talk will discuss two experiments demonstrating that single cycle optical fields at optical frequencies allow manipulating electronic and spin degrees of freedom in solid state systems at optical clock rates faster than de-coherence. Ultrafast bidirectional energy transfer between a light-field and the band-structure of silica proves the early times reversibility of electronic excitations and holds promise of novel ultrafast, coherent optoelectronic applications.

As a corollary of this ultrafast coherent modification of the electronic system, in suitably chosen herterostructures also the spin system can be manipulated coherently. Optically induced spin transfer is demonstrated as a route to the direct, all-optical manipulation of macroscopic magnetic moments on previously inaccessible attosecond timescales.

**15 min. break.**

**Invited Talk** SYAS 1.4 Mon 16:45 HSZ 02

**All-coherent subcycle switching of spins by THz near fields** — •Christoph Lange — Department of Physics, University of Regensburg, Regensburg, Germany

As state-of-the-art electronics encounters ultimate limits, novel concepts for harnessing coherent charge and spin dynamics in solid-state systems are being sought after. Atomically strong, phase-locked electromagnetic waveforms in the terahertz (THz) spectral range with photon energies far below typical interband excitations have facilitated lightwave acceleration of charges in bulk semiconductors, leading to dynamical Bloch oscillations and high-harmonics generation. Moreover, strong THz fields have driven inertia-free, ballistic currents of Dirac fermions of topological surface states of $Bi_2Te_3$ over mesoscopic distances, moving lightwave-electronic devices into practical reach. In contrast, subcycle control of the spin degree of freedom is much more challenging due to the intrinsically lower coupling of optical fields to magnetic excitations. We exploit a novel electric-dipole mediated mechanism to induce unprecedentedly large spin oscillations in the antiferromagnet $TmFeO_3$. Strong, single-cycle THz pulses are enhanced by a custom-tailored, micrometer-sized metallic antenna fabricated on top of a bulk $TmFeO_3$ sample, where the antenna's atomically strong near fields change the magnetic anisotropy on a subcycle scale. The resulting spin dynamics include a characteristic phase flip, an asymmetric spectral splitting of the magnon resonance, and a long-lived offset of the polarization rotation signal, representing a novel fingerprint of all-coherent spin switching with minimal energy dissipation.

**Invited Talk** SYAS 1.5 Mon 17:15 HSZ 02

**Ultrafast optically-induced spin transfer in ferromagnetic alloys** — •Stefan Mathias — I. Physikalisches Institut, Georg-August-Universität Göttingen, 37077 Göttingen, Germany

The idea of using light to manipulate electronic and spin excitations in materials on their fundamental time and length scales requires new approaches in experiment and theory, to observe and understand these excitations. The ultimate speed limit for all-optical manipulation requires control schemes for which the electronic or magnetic sub-systems of the materials are directly manipulated on the timescale of the laser excitation pulse. In our work, we provide experimental evidence of such a direct, ultrafast optically-induced spin transfer between two magnetic subsystems in an alloy of Fe and Ni [Hofherr et al., Science Adv. 2019, in press] and various Heusler compounds.