Scientific goal of the project

The waves in nanostructures can be used to transmit and process the information. The wave dynamics are molded both by the proper design of the structure and the selection of the material parameters. The geometrical constraints can be adjusted quite freely. The role of geometry is well known, and results obtained for the waves of a given kind can usually be generalized. On the contrary, the meaning of material parameters is specific for a particular kind of waves and can be changed in a limited range related to accessible materials. The interplay between the geometry and material composition is crucial at the surfaces and interfaces. One of the quite obvious effects is the local change of material parameters. However from the fundamental point of view, more significant and more interesting is the impact of this relation on the boundary conditions. The role of the surface/interface effects is ever more pronounced when they mediate the interaction between two kinds of waves of different physical nature in two coupled subsystems of hybrid structure.

The state of the surfaces affects the freedom of the magnetization at the boundaries of the magnetic medium. It is observed as partial pinning spin wave dynamics at the surfaces, which then modifies the quantization of the spin waves in the interior of the magnetic medium. This mechanism is, to some extent, similar to the adjustments of the geometrical sizes of the system. Therefore it is equally important for tailoring the magnetization dynamics. However, its origin is complex. It has a local component because it can be tuned by the change of the physical state (breaking bound and reducing the coordination number) and chemical state (oxidation) of the surface. These processes ultimately modify the spin-orbit infractions and change the energy of magnetic moments at the surface, expressed quantitatively as surface anisotropy constant. Except for this local mechanism (i.e., called surface anisotropy), there is also the non-local component related to the impact of the long-range dipolar interaction, sensitive to the presence of the surfaces. The dipolar interaction in planar nanostructures can, equally as the surface anisotropy, lead to the spin waves pinning. Therefore the impact of the surface anisotropy on spin wave pining must always be investigated together with the dipolar mechanism of pinning.

The magnonic systems (nanostructures supporting the spin wave dynamics) can be combined by magnetoelastic interaction with phononic systems (processing the elastic waves) or by the electromagnetic coupling with superconducting structures (where the superconducting eddy currents generate magnetic stray field). In these hybrid structures, the impact of the surface anisotropy seems to be very important for the boundary condition of combined excitations: (i) magnetoelastic waves or (ii) spin waves coupled to eddy currents. Moreover, the spin waves pinning resulting from the surface anisotropy will affect the spatial cross-section of elastic waves and spin waves (for magnonic-phononic hybrids) or dynamic magnetic fields produced by spin wakes and eddy currents (for magnonic-superconducting hybrids).

The main scientific goal of the project is to **investigate the impact of surface anisotropy on the interaction between spin waves and elastic waves (or eddy currents) in hybrid magnonic-phononic (and magnonic-superconducting) structures**.
The research hypothesis is that the **surface anisotropy can change the conditions at the interface between magnonic and non-magnonic components of hybrid system boundary for dynamic excitation**. We think this opened the possibility to tailor the coupling between spin waves and non-magnetic excitations by changing the state of the interface between the subsystems in a hybrid structure.

Significance of the project

The magnonic devices which operate on spin waves are very promising candidates to perform wave-based computing [Mahmoud20]. However, their potential can be significantly extended in hybrid systems where the magnonic subsystem is combined with a phononic or superconducting one. Due to the interaction between spin waves and surface acoustic waves [Babu20, Godejohann20, Geilen20, Xu20] or the coupling between spin waves and the stray field of superconducting eddy currents [Golovchanskiy18, Golovchanskiy20, Dobrovolskiy19], we can then significantly extend possibilities for spin wave processing because we can steer the spin waves by non-magnetic means.

As opposed to elastic waves or electromagnetic waves (stray field), spin waves are constrained strictly to ferromagnetic medium. Therefore, the magnetization dynamics on the interface is essential for the coupling. The boundary condition also determines the dynamics of magnetization inside the magnetic medium and affects the cross-section between the spin waves and the wave of other kinds that can penetrate the magnetic medium. One of the most important(critical) parameters affecting the boundary conditions for magnetization is surface anisotropy energy density.

The surface anisotropy interplayed with the shape anisotropy (i.e. dipolar effects) can tailor the magnetic configuration and magnetization dynamics in planar magnonic structures [Mohseni20, Centala19, Klos18, Banerjee17]. Moreover, in hybrid systems, we gain the possibility for the controlling of anisotropy by strain [Shelukhin20] or electric field [Xu20] and then steer the spin waves indirectly (i.e., via changes of anisotropy).

In our studies, **we are going to focus on the <u>impact of surface anisotropy</u> (and dipolar effect) on magnetization <u>dynamics</u> in hybrid systems**. The theory of spin wave pinning (induced by the combined effect of surface anisotropy and demagnetizing fields) was developed by Konstantin Guslienko [Guslienko05] for planar magnetic nanoelements. His theory was verified experimentally and numerically [Bayer05, Centala19]. We believe that it can be extended to a more general case where also the impact of (i) the effective magnetic field of magnetoelastic origin [Dreher12] or (ii) the stray field produced by eddy currents [Dobrovolskiy19] will be taken into account to calculate the pinning of the dynamic component of magnetization at the interface. This approach will allow initiating the extensive studies on the combined role of the local characteristic of the interface (surface anisotropy) and the non-local influence (of effective magnetic fields produced by other dynamic excitations) on the spin waves dynamics in hybrid nanostructures. The solution of our scientific hypothesis will give a better understanding of the wave dynamics in hybrid nanostructures (magnonic-phononic and magnonic-superconducting):

- we are going to provide the theoretical model and perform the numerical studies on the wave interaction in hybrid systems in the presence of surface anisotropy,
- we would like to point the new ways for tailoring the interaction in hybrid systems by spatial changes of the surface anisotropy.

Ultimately, we aim to acquire new knowledge useful for **designing the nanodevices by playing with the material characteristics of the interfaces in nanoscale**.

Concept and work plan

In the project, we planned four tasks for the four years of Ph.D. studies. The tasks are described in the order in which they will be realized in the project. We assume that all tasks should be completed within three and a half years. The theoretical studies for Task 1 and Task 3 will be done in cooperation with prof. Konstantin Guslienko during the internship of the Ph.D. student. Tasks 1,2,4 have the optional experimental parts, which will be realized in cooperations with international partners (Task 1 – University of Greifswald and Task 4 – University of Vienna) or using the experimental facilities at Adam Mickiewicz University (AMU).

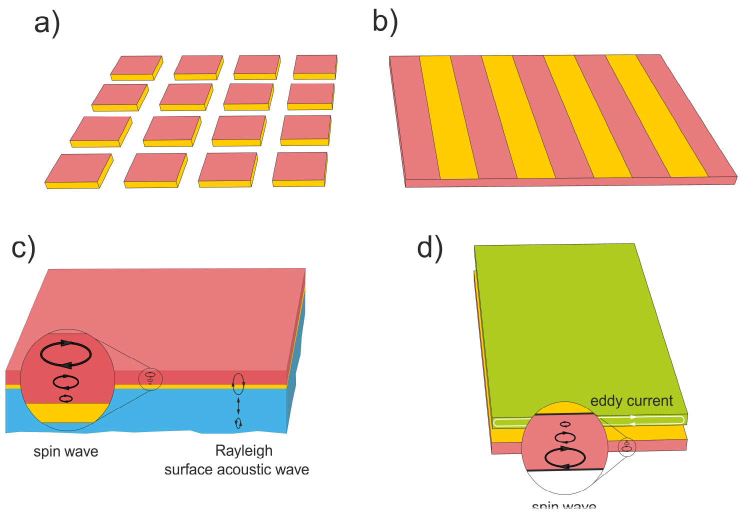

Fig.1. *The structures illustrating Tasks of the project (red – ferromagnet, green superconductor, blue – non-magnetic substrate, yellow – regions of modified magnetic anisotropy). Task 1. upshift of the FMR frequency due to the spin wave pinning. Task 2. Formation of magnonic crystal. Task 3. Magonic-phononic hybrid with the magnetic anisotropy at the interface. Task 4. Magnonc-superconducting hybrid with magnetic anisotropy on one face of the ferromagnetic layer*

Task 1. **Controlling the ferromagnetic resonance frequency in magnetic metamaterials**

We are going to consider the ferromagnetic plane patterned periodically in one or two dimensions to form the array of flat stripes or dots. In our previous studies [Centala20], we found the spin wave pinning at lateral edges of the flat stripes resulting both from the dipolar effects and the modification of the anisotropy at edges. Our numerical studies were recently confirmed by meassuring ferromagnetic resonance frequency using the time-resolved magnetooptical Kerr effect (TR-MOKE) spectrometry (at Greifswald University). We found that by changing the distance between the stripes, we can tune the dipolar contribution to spin wave pinning and gradually change the ferromagnetic resonance (FMR) frequency. Basing on these preliminary results, we plan to extend our studies in the following way:

- develop the theory describing the pinning parameter [Guslienko02] for 1D and 2D patterns of the nanoelements including the impact of the surface anisotropy,
- determine numerically the value of the FMR frequency treating the patterned layer as a metamaterial (for wave vector k=0) and compare this results to the TR-MOKE measurements, performed for CoFeB samples from resources of the group form Greifswald.

Task 2. **Induction of magnonic crystal in a pristine magnetic layer by periodically surface anisotropy**
We plan to investigate the spin wave propagating in the homogeneous magnetic layer where the surface anisotropy changes in a periodic manner on one face of the layer. Such a system can be practically realized by the oxidation of the top surface of the magnetic layer through the mask which hides and expose the complementary parts of the surface. We expect to induce the magnonic crystals where the spin waves can propagate in the range of magnonic bands with relatively high group velocity and experience the periodicity due to modulated surface anisotropy on one face of the layer. The analytical and numerical studies will be focused on:

- the determination dispersion relation (and the position of frequency gaps) in the dependence on the strength of the anisotropy and its geometrical parameters (period, filing fraction) - we are going to consider the patterns of surface anisotropy with the periodicity in one or two dimensions,
- the analysis of non-reciprocal spin-wave transmission, expected for Damon-Eshbach configuration (static magnetization perpendicular to the wave vector)
- spin wave guiding along with the linear defect in 2D surface anisotropy pattern, for the frequencies in the range of the magnonic gap.

Task 3. **Impact of surface anisotropy on the magnetoelastic interaction in the magnetic layer**
The goal is to extend our current studies concerning the magnetoelastic interaction between the surface acoustic waves and spin waves to investigate the role of magnetic anisotropy. The system we are going to investigate will be composed of the magnetostrictive (multilayer, e.g., CoFeB/Au) deposited on the nonmagnetic substrate. We will consider the substrate (e.g., MgO), which can induce the surface anisotropy on the interface with multilayer (i.e., at the CoFeB/MgO interface). We expect that the role of the surface anisotropy will be twofold (i) it will change the profile of fundamental and perpendicularly standing spin waves within the (multi)layer to asymmetric one and thus modify the cross-section surface acoustic waves and spin waves, (ii) it will modify the magnetoelastic boundary conditions. We are going to perform the following studies:

- extend the current model of magnetoelastic interaction and introduce the magnetoelastic boundary conditions instead of the independent boundary conditions for the dynamic components of magnetization and elastic displacement – we expect that this modification will give some noticeable correction to the calculations for the (anti)crossings in magnetoelastic dispersion relation,
- formulation of the magnetoelastic boundary condition which takes into account the surface anisotropy and the calculation of magetoelastic dispersion relation,
- Brillouin light scattering measurement for the samples with surface anisotropy in magnetic (multi)layer, done by AMU group.

Task 4. **Role of surface anisotropy for the shaping of magnetization dynamics in hybrid ferromagnet-superconductor nanostructures**
We are going to find how the surface anisotropy for ferromagnetic magnetic stripe affects the coupling between eddy current dynamics in a superconductor (described by London equations) and magnetization dynamics in a ferromagnet (described by Landau-Lifshitz equation). Considered hypothesis is that the coupling between the magnetization and eddy currents can change if we pin the magnetization on the interface and those change the dynamic demagnetizing field produced by processing magnetization, which influences eddy currents. We will consider a hybrid structure composed of a permalloy stripe covered by a superconducting stripe in Meissner state, made of niobium. To cancel the proximity effects between the ferromagnet and superconductor, a few nanometer thick dielectric spacer will be placed. The aims of this task are:

- determine the numerically and analytically the pinning parameter for in the presence of stray field produced by superconducting stripe,
- include the surface anisotropy on the interface with insulating spacer and check its impact on the coupling between eddy currents and spin waves,
- interpret the microwave spectroscopy results in a low temperature will be performed by the group from Vienna.

Risk analysis
Task 1 is based on preliminary results concerning both the numerical outcomes and experimental results. The numerical studies for more complex geometries (2D patterns) are quite straightforward (the risk is very low). The development theory for spin wave pinning in challenging but it will be done in the collaboration with the expert in this field. The experimental part is solely on the side of the group involved in international cooperation (Greifswald).

Task 2 is a purely numerical study focusing only on the spin wave dynamics – risk related to the complement of the task is relatively low.

Task 3 - the realization of this task is riskier. However, is based on previous results [Babu20] and the numerical/theoretical parts should be completed without serious difficulties. The sample will be fabricated by the collaborating group from Institute of Molecular Physics (IMP), PAS (which co-authored the paper [Babu20]). The sample will be passed to AMU to complete the measurements using Brillouin Light Scattering (BLS).

Task 4 – is the most challenging because it requires the development of a new formalism. The risk related to the realization of the task is moderate. The measurements will be performed by an experienced experimental group from Vienna University (international cooperator) which will use their samples.

Preliminary results

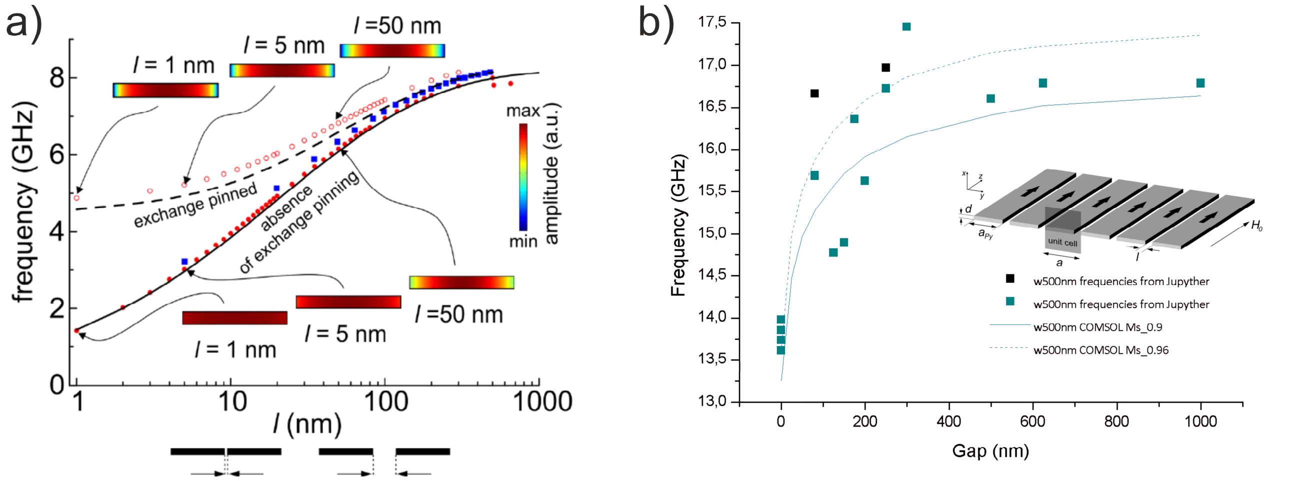

Fig.2. *The impact of the surface anisotropy (on the lateral edges of ferromagnetic stripes) and dipolar effects on the FMR frequency. (a) Numerical results [Centala19] and (b) preliminary experimental outcomes (TR-MOKE – in Greifswald) showing the dependence of FMR on the distance between stripes.*

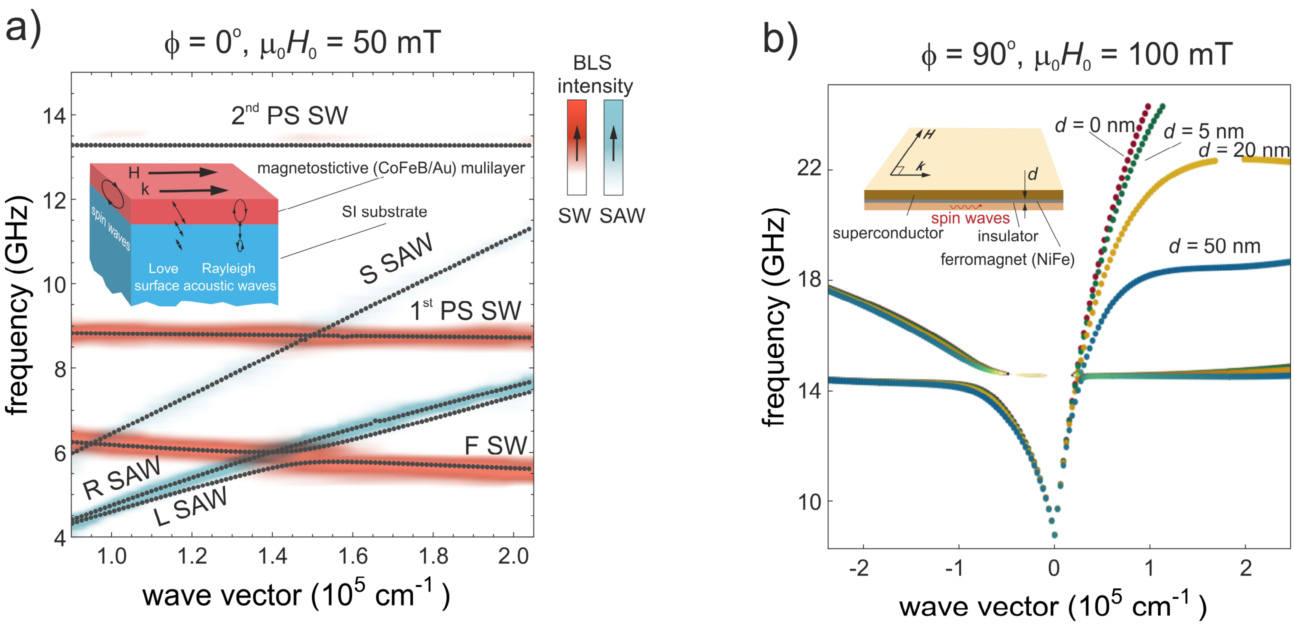

Fig.2. *(a) Magnetoelastic dispersion relation was calculated by the finite element method (gray dots) and measured using Brillouin light spectrometry in AMU [Babu20]. We can see the interaction (anticrossing) between Love surface acoustic wave (L SAW) wave and the fundamental spin-wave (FSM) mode, whereas the Rayleigh surface acoustic waves (R SAW) do not interact with spin waves. (b) Spin wave dispersion relation in the ferromagnetic layer covered by the superconductor, calculated by the finite element method (please note the evident non-reciprocity in the dispersion relation $\omega(k)\neq\omega(-k)$). The superconductor was treated as a perfect conductor which was reflected in the electromagnetic boundary conditions (for magnetic field) at the interface. The impact of the eddy current was not included yet. For both studies (a) and (b) the surface, anisotropy is not included.*

Research methodology

Numerical simulations – simulations will be performed using the finite element method and the COMSOL Multiphysics environment with the acoustic module. We will run the computations using the workstations, equipped with a large amount of RAM (128 GB). The COMSOL calculations will be performed using our own–developed scripts.

Data postprocessing, symbolic computations, editing manuscript – we will use the Python codes and Wolfram Mathematica scripts to post-process numerical data, generate the figures and perform some symbolic calculations. The manuscripts will be edited using the Overleaf online repository.

Sample fabrication and measurements – fabrication: magnetron sputtering (in argon, in a multi-chamber system IMP, PAS), measurements: BLS (wavelength 532 nm, six-pass tandem Brillouin spectrometer TFP2-HC – AMU), TR-MOKE (central wavelength of 800 nm, with a repetition rate of 250 kHz, pulse energy of about 1 μJ/pulse, and 50 fs pulse duration - Greifswald), microwave spectroscopy (temperature range: 10 mK – 300 K -Vienna).

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