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Report on potential of other spin structures (double layers, SAFs, skyrmionic bubbles)

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Authors: Gerhard Jakob, Mathias Kläui

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1. Potential of other spin structures (Double layers, Synthetic antiferromagnets, Skyrmionic bubbles, Stochastic magnetic tunnel junctions)

1.1. Starting point and literature survey

NIMFEIA aims to provide a hardware solution for brain-inspired computing using magnetic materials on the nano-scale, combined with advanced spintronics technologies. It is based on the disruptive idea of reciprocal-space computing, utilizing nonlinear interactions of quantized magnetic excitations. In the presence of nontrivial spin structures, such as magnetic vortices, these nonlinear interactions can be efficiently harnessed for reservoir computing tasks like pattern recognition and time-series prediction with minimal pre-processing of input data. By making use of quantum interactions in reciprocal space, computing is done in individual spatially confined devices, such as a single magnetic disc, without the need to transport information in real space. HZDR demonstrated this nonlinear transfer of energy between spin-wave eigenmodes in magnetic vortex structures [1,2]. The potential of magnon reservoir technology was disclosed as invention to the innovation managers and technology transfer division at the partner HZDR in June 2021 and the patent granted in 2023 [3].

Since the mid-2010s, there has been growing recognition that the inherent nonlinearity in magnetisation dynamics can be an asset for neuro-inspired computing. One pioneering work relied on the amplitude dynamics of vortex-based spin-torque nano-oscillators to implement a form of *reservoir computing*, a neuro-inspired paradigm in which the evolution of a dynamical system is exploited to perform computation, which was used to perform spoken digit recognition [4]. This idea has been explored using other magnetic phenomena, such as random skyrmion structures [5], arrays of spin-torque nano-oscillators [6], artificial spin ice [7], time-delay architectures [8], or modulations with a single oscillator [9], and so on. Proposals involving oscillator arrays necessarily rely on a real-space network structure, where physical concerns constrain the number of connections between nodes (artificial neurons) from 10^1 to 10^2 at best, which is far from the typical 10^5 synapses attached to each neuron in the human brain. Time-delay approaches map the network structure into the time domain, where similar challenges arise since the device output needs to be continually sampled and fed back into the nonlinear node, limiting the effective connectivity to the same range of 10^1 to 10^2. A different non-conventional computing scheme is token-based Brownian computing. For the latter, a novel layout was developed that can speed up the computation significantly and avoids real-space intersections that make fabrication difficult [10]. Furthermore, by combining natural thermal diffusion with an induced artificial diffusion, the scope of applications can be broadened significantly. The ideas have been submitted as a patent disclosure [11].

A further thread followed in the community for non-conventional computing is to exploit stochasticity. Especially, superparamagnetic magnetic tunnel junctions can be exploited for that idea, as demonstrated by Camsari et al. [12]. The fluctuating p-bit represents not just a 0 or 1 but an arbitrary tuneable value in between. This mimics the properties of quantum bits, but the entanglement is missing. Such they are nicknamed “poor man’s q-bits”. In spite of the missing entanglement, the fast fluctuations enable to probe a vast phase space in short time, and they can potentially speed up the solution of NP hard problems by orders of magnitude. In contrast to q-bits, mass scale production and integration of magnetic tunnel junctions are established from MRAM production. Therefore, this is another promising spintronic idea for exploiting spin structures in non-conventional computing.

1.2. Strategy and Methods

While, as described before, there are numerous spintronic-based ideas to implement non-conventional computing, we focused within NIMFEIA on three threads that fit best to the know-how of the consortium. The main idea, doing nonlinear computing in reciprocal space, is reported in other reports of NIMFEIA. In this report we focus on skyrmions and superparamagnetic tunnel junctions.

We recognized early that our skyrmionics systems could be exploited for non-conventional computing approaches, such as reservoir computing. Magnetic skyrmions, topological particle-like spin textures in magnetic films are particularly promising for implementing reservoir computing, since they respond in a strongly nonlinear way to external stimuli and feature inherent multiscale dynamics. We proposed and experimentally demonstrated a conceptually new approach to skyrmion reservoir computing that leverages the thermally activated diffusive motion of skyrmions. By confining the electrically driven and thermally assisted skyrmion motion in a suitable lateral structure, we demonstrated that already a single skyrmion in a confined geometry suffices to realize even a not linearly separable XOR gate, along with all other Boolean logic operations. Besides this universality, the reservoir computing concept ensures low training costs and ultra-low power operation with current densities orders of magnitude smaller than those used in existing spintronic reservoir computing demonstrations. Our proposed concept is robust against device imperfections and can be readily extended by linking multiple confined geometries and/or by including more skyrmions in the reservoir, suggesting high potential for scalable and low-energy reservoir computing. This realization of the logic operations was published in Nature Communications in 2022 [A]. This breakthrough result led to the invitation to the perspective article: 'Perspective on unconventional computing using magnetic skyrmions' in Applied Physics Letters [B]. Such 'Perspectives' articles are initiated by the editors of the journal if they think a new and interesting field will open and they want to highlight these new research directions and give them broad visibility.

While in this initial work we only used one skyrmion in a confined geometry, it is evident that more skyrmions and modified geometries lead to enhanced complexity and need to be characterized and finally exploited.

The knowledge we had gained in [A] on driving the skyrmion by currents in a confined geometry we applied to develop a rotation counter-sensor device. We created a concept for a multiturn counter-sensor device based on skyrmions, where the number of sensed rotations is encoded in the number of nucleated skyrmions. The skyrmion-boundary force in the confined geometry of the device in combination with the topology-dependent dynamics leads to the effect of automotion for certain geometries. We described and investigated this effect with micromagnetic simulations and the Thiele equation in a triangular geometry with an attached reservoir as part of the counter-sensor device. We explored the device functionality, taking into account the influence of thermal diffusion. Additionally, we analysed a readout mechanism for the skyrmion storage, capable of quantifying skyrmion numbers and working effectively even in the presence of thermal diffusion. Finally, our investigation studied the deterministic nucleation of skyrmions. While this work, which is published in Physical Review Applied [C], focuses on the sensor application, it directly profited from knowledge built up in NIMFEIA and discussions between participating scientists.

Going from a single skyrmion in confined geometry to a lattice of skyrmions was more complex than anticipated. Skyrmions show Brownian motion and lattice formation in two dimensions. They follow an equation of motion, the Thiele equation, which includes a topology-dependent chiral term, linear in velocity, causing a skyrmion Hall effect and a drastic reduction of the diffusion coefficient for individual skyrmions, as compared to normal Brownian particles. Using Brownian-dynamics simulations, we showed that this topological suppression of the diffusion can be partially lifted in two-dimensional lattices of skyrmions. Counterintuitively, this causes enhanced diffusive properties with increasing particle density, similar to odd-diffusive Brownian particles. We showed how the topological charge of the skyrmions influences the dynamics of topological lattice defects, which also affects the dynamics of the phase formation. The numerical study of the skyrmion dynamics in confined geometry is published in Physical Review Research [D].

Our experimental mapping of skyrmion trajectories by magneto-optical Kerr effect microscopy and the above-discussed numerical simulations have shown that thermally activated skyrmions in confined geometries arrange predominantly based on commensurability effects. As the understanding of skyrmion dynamics in confinements is necessary for device applications, we performed a simulation study, based on the Thiele model, to investigate the enhanced dynamics and degenerate non-equilibrium steady state of a system in which the intrinsic skyrmion–skyrmion and skyrmion–boundary interaction compete with thermal fluctuations as well as current-induced spin–orbit torques. The investigated system was a triangular-shaped confinement geometry hosting four skyrmions, where we injected electrical currents between two corners of the structure. We coarse grained the skyrmion states in the system to analyse the intricate arrangements of the skyrmion ensemble that emerge for each current density. In the context of neuromorphic computing, such methods address the key challenge of optimizing the positions for an electrical readout in confined geometries and form the basis for understanding collective skyrmion dynamics in systems with competing interactions on different scales. The details of this work are published in Physical Review Research [E]. The task of optimization of the readout position of magnetic tunnel junction on top of the dynamic spin structure is essential also for the nonreciprocal computing in the main thread of NIMFEIA.

For device operation, the detection of the position, shape, and size of skyrmions is required and magnetic imaging is typically employed. We predominantly use magneto-optical Kerr microscopy for skyrmion detection, e.g. to obtain the experimental data used in [A] and [E]. Depending on the sample's material composition, temperature, material growth procedures, etc., the measurements suffer from noise, low contrast, intensity gradients, or other optical artifacts. Conventional image analysis packages required manual pre and post treatment, and a more automatic solution was required. We developed a convolutional neural network based on U-Net that is specifically designed for segmentation problems and capable to detect the position and shape of all skyrmions in our measurements. The network was tuned using selected techniques to optimize predictions and, in particular, the number of detected classes was found to govern the performance. The results of this study showed that a well-trained network is a viable method of automating data preprocessing in magnetic microscopy. The approach is easily extendable to other spin structures investigated within NIMFEIA and other magnetic imaging methods. This automatic image processing algorithm and its exemplarily application is published in Physical Review Applied [F], the full training dataset of 2400 Kerr micrographs is shared via Zenodo [https://doi.org/10.5281/zenodo.10997175], and a tutorial session held at the 2025 Spring Meeting of the German Physical Society that is available on GitHub [https://github.com/kfjml/AI-Magnetism-Session-Regensburg-2025].

The successful application of the know-how gathered on skyrmion dynamics in confined geometries culminated in the gesture recognition using reservoir computing, based on a skyrmionic system and is published in Nature Communications [G]. By time-multiplexed skyrmion reservoir computing we aligned the reservoir's intrinsic timescales to real-world temporal patterns. Using millisecond-scale hand gestures recorded with Range-Doppler radar, we fed voltage excitations directly into our device and detected the skyrmion trajectory evolution. This method scales down to the nanometer level and demonstrates competitive or superior performance compared to energy-intensive software-based neural networks. Our hardware approach's key advantage is its ability to integrate sensor data in real-time without temporal rescaling, enabling numerous applications. For more details we refer here to the separate report on recognition task within NIMFEIA or the published article that is freely available.

As a second, alternative, spin structure for non-conventional computing, we investigated superparamagnetic tunnel junctions (SMTJs). This directly connects to the tasks of reading the dynamic state of the vortex disks in NIMFEIA's nonreciprocal computing. The essential difference is that the MTJs need to be stable there, but unstable and stochastic due to thermal fluctuations for the purpose here. The stability of a magnetic tunnel junction can be tuned by the size, shape, and magnetic anisotropy of the free layer and further modified by external magnetic fields and temperature. We investigated nanosecond superparamagnetic switching in 50-nm-diameter in-plane magnetized magnetic tunnel junctions (MTJs). Due to the small in-plane uniaxial anisotropy, dwell times below 10 ns and autocorrelation times down to 5 ns were measured for circular superparamagnetic tunnel junctions. SMTJs exhibit probabilistic switching of the magnetic free layer, which can be used for the generation of true random numbers. The quality of the random bit streams generated by our SMTJs was evaluated with a statistical test suite and showed true randomness after three XOR operations of four random SMTJ bit streams. A low-footprint CMOS circuit was proposed for fast and energy-efficient random-number generation. We demonstrated that the probability of a 1 or 0 can be tuned by spin-transfer torque (STT), while the average bit-generation rate was mainly affected by the current density via Joule heating. Although both effects are always present in MTJs, most often Joule heating is neglected. However, with a resistance-area (RA) product of 15 μm^2 and current densities of the order of 1 MA/cm^2, an increasing temperature at the tunnelling site results in a significant increase in the switching rate. As Joule heating and STT scale differently with current density, the device design can be optimized based on our findings that have been published in Physical Review Applied [H].

Being successful in the investigation of individual SMTJs, the next step was to couple SMTJs electrically. We studied the effect of electrical coupling on stochastic switching of two in-plane SMTJs, using experimental measurements as well as simulations. The coupling mechanism relies on the spin-transfer-torque effect, which enables the manipulation of the state probability of an SMTJ. Through the investigation of time-lagged cross-correlation, the strength and direction of the coupling were determined. In particular, the characteristic state probability transfer curve of each SMTJ leads to the emergence of a similarity or dissimilarity effect. The cross-correlation as a function of applied source voltage revealed that the strongest coupling occurs for high positive voltages for our SMTJs. In addition, we showed state tunability as well as coupling control by the applied voltage. The experimental findings of the cross-correlation agree with our simulation results. This research was published in Applied Physics Letters [I].

Based on the sigmoidal response function of the SMTJs and the true randomness we exploited with partners this functionality for non-conventional computing. There the stochasticity of the junction was used to mimic noise that is always present in biological systems. Brain-inspired learning in physical hardware has enormous potential for rapid learning with minimal energy expenditure. One of the characteristics of biological learning systems is their ability to learn in the presence of various noise sources. Inspired by this observation, we introduced a noise-based learning approach for physical systems implementing multilayer neural networks. Simulation results show that our approach allows for effective learning with a performance approaching that of the conventional backpropagation algorithm, which is effective but has a high energy cost. Using a spintronics hardware implementation based on SMTJs, we demonstrated experimentally that learning can be achieved in a small network composed of physical stochastic magnetic tunnel junctions. These results provide a path toward energy-efficient learning in general physical systems that embraces rather than mitigates the noise inherent in physical devices. This research was published as Editor's suggestion in Physical Review Applied [J].

1.3. Summary and conclusions

In conclusion, our investigation of other spin structures was very successful. Both ideas picked up were fruitful. With the skyrmion based idea we could even demonstrate the working principle of gesture recognition based on skyrmion dynamics. For the SMTJs the data generated within NIMFEIA could be used to benchmark successfully a new algorithm for machine learning. More detailed results than mentioned in this report can be found in the scientific papers that are published with NIMFEIA acknowledgements in [A] - [J]. These papers discuss also topics that go beyond the scope of NIMFEIA.

2. Publications

[A] **Brownian reservoir computing realized using geometrically confined skyrmion dynamics,** Raab, K., M. A. Brems, G. Beneke, T. Dohi, J. Rothörl, F. Kammerbauer, J. H. Mentink, and M. Kläui, Nature Commun 13, 6982 (2022), https://doi.org/10.1038/s41467-022-34309-2

[B] **Perspective on unconventional computing using magnetic skyrmions**, Lee, O., R. Msiska, M. A. Brems, M. Kläui, H. Kurebayashi, and K. Everschor-Sitte, Appl. Phys. Lett. **122**, 260501 (2023), https://doi.org/10.1063/5.0148469

[C] **Skyrmion automotion and readout in confined counter-sensor device geometries**, Leutner, K., T. B. Winkler, R. Gruber, R. Frömter, J. Güttinger, H. Fangohr, and M. Kläui, Phys. Rev. Appl. **20**, 064021 (2023), http://dx.doi.org/10.1103/PhysRevApplied.20.064021

[D] **Two levels of topology in skyrmion lattice dynamics**, Daniel Schick , Markus Weißenhofer, Levente Rózsa, Jan Rothörl, Peter Virnau, and Ulrich Nowak Phys. Rev. Research **6**, 013097 (2024), https://doi.org/10.1103/PhysRevResearch.6.013097

[E] **Coarse-graining collective skyrmion dynamics in confined geometries.** Winkler, T. B., J. Rothörl, M.A. Brems, G. Beneke, H. Fangohr, and M. Kläui, Appl. Phys. Lett. **124**, 022403 (2024), https://doi.org/10.1063/5.0187446

[F] **Machine-learning-based detection of spin structures**, Labrie-Boulay, I., T. B. Winkler, D. Franzen, A. Romanova, H. Fangohr, and M. Kläui, Phys. Rev. Appl. **21**, 014014 (2024), https://doi.org/10.1103/PhysRevApplied.21.014014

[G] **Gesture recognition with Brownian reservoir computing using geometrically confined skyrmion dynamics,** G. Beneke, T.B. Winkler, K. Raab, M.A. Brems, F. Kammerbauer, P. Gerhards, K. Knobloch, S. Krishnia, J.H. Mentink, and M. Kläui, Nature Commun. **15**, 8103 (2024), https://doi.org/10.1038/s41467-024-52345-y

[H] **Nanosecond True Random Number Generation with Superparamagnetic Tunnel Junctions - Identification of Joule Heating and Spin-Transfer-Torque effects**, Schnitzspan, L., M. Kläui, and G. Jakob, Phys. Rev. Appl. **20**, 024002 (2023), https://doi.org/10.1103/PhysRevApplied.20.024002

[I] **Electrical coupling of superparamagnetic tunnel junctions mediated by spin-transfer-torques**, Schnitzspan, L., M. Kläui, and G. Jakob, Appl. Phys. Lett. **123**, 232403 (2023), https://doi.org/10.1063/5.0169679

[J] **Noise-based local learning using stochastic magnetic tunnel junctions,** Kees Koenders, Leo Schnitzspan, Fabian Kammerbauer, Sinan Shu, Gerhard Jakob, Mathias Kläui, Johan H. Mentink, Nasir Ahmad, and Marcel van Gerven, Phys. Rev. Appl. **23**, 054035 (2025), http://dx.doi.org/10.1103/PhysRevApplied.23.054035

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