83rd International Scientific Conference of the University of Latvia 2025

Section

Active, Soft, and Magnetic Matter

Book of Abstracts

Tuesday, 28 January 2025 | 14:00 (Riga Time) | Hybrid Format
House of Science, University of Latvia

UNIVERSITY OF LATVIA

Magnētisku Mīkstu Materiālu Laboratorija
LAB OF MAGNETIC SOFT MATERIALS

Active, Soft, and Magnetic Matter

Tuesday, 28 January 2025 | 14:00 (Riga Time)
House of Science, University of Latvia – Room ZM, 804
Online: via Zoom

Programme

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16.28–16.40	***Andris P. Stikuts***	**Engineering tunable fractional Shapiro steps in colloidal transport**	p.12
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Exploring Vortex-Vortex Correlations in Dry Active Matter

Jorge Coelho
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It was recently shown that wet active matter can form synchronized rotating vortices in a square lattice, similar to an antiferromagnetic Ising model (by considering rotation direction as spin projection). In this study, we investigate whether such a correlated state occurs for a model of dry active matter. We achieve that by numerically simulating the dynamics of a system of active particles in the presence of two identical circular obstacles. Then, we measure the angular velocity correlation function of both vortices as a function of the obstacle diameter, their shortest separation (gap), and the particle density. When the correlation function is negative, both vortices rotate in contrary directions. They maintain this state by exchanging particles through the region between them, analogously to synchronized cogs. On the other hand, with a positive correlation function, a single rotating cluster emerges, and the particles move around the whole structure, similar to a belt strapped around the obstacles. Additionally, we observe the emergence of uncorrelated states at the transition between correlated states, in which only a single vortex is present, or in the large gap regime, in which the vortices are nearly independent of each other [1].

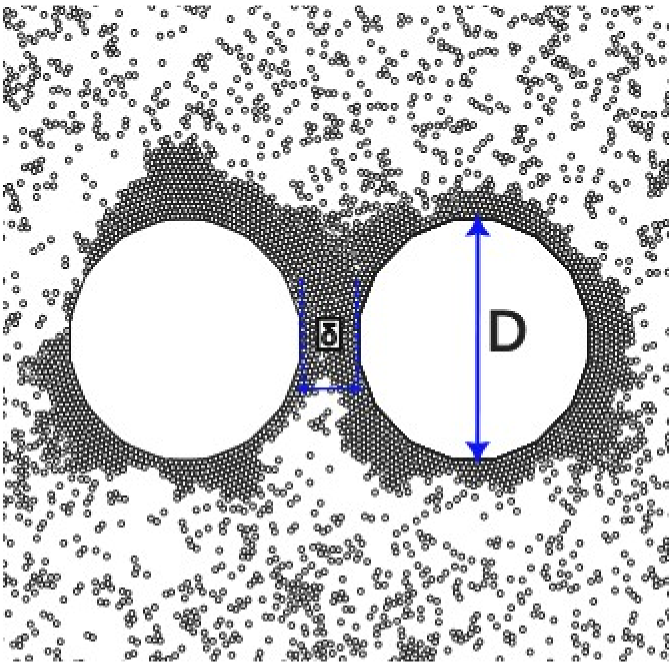

Figure 1. Typical particle configuration for our two obstacle system of diameter D and separated by a gap δ.

References

[1] P. S. Felipe Júnior, J. L. C. Domingos, F. Q. Potiguar, and W. P. Ferreira, *Physica A: Statistical Mechanics and its Applications* 656, 130181 (2024).

Defect formation in expanding ensemble of spinners

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We investigate a two-dimensional ensemble of spinners that forms a hexagonal ordered state, giving rise to defect chains in the ordered structure when hydrodynamic interactions and repulsion between the spinners are considered [1]. The defect chains emerge during the expansion of the spinner ensemble due to topological reasons. These defects in the hexagonal structure appear at n_+ sites with 5 (green) and n_- sites with 7 (red) nearest neighbors, as illustrated in Fig. 1. Over time, as the ensemble evolves to an ordered state, the difference $n_+ - n_-$ diminishes and stabilizes at a constant value of 6 due to topological constraints. We study the characteristics of the expansion of the ensemble. It is observed that the expansion rate of the ensemble varies depending on the interaction parameter. To analyze this in detail, we calculate the radial velocity of spinners located at the boundary of the ensemble. For a specific range of interaction parameters, we observe a constant expansion rate. Numerical simulations of the ensemble's expansion are compared with a theoretical expansion model.

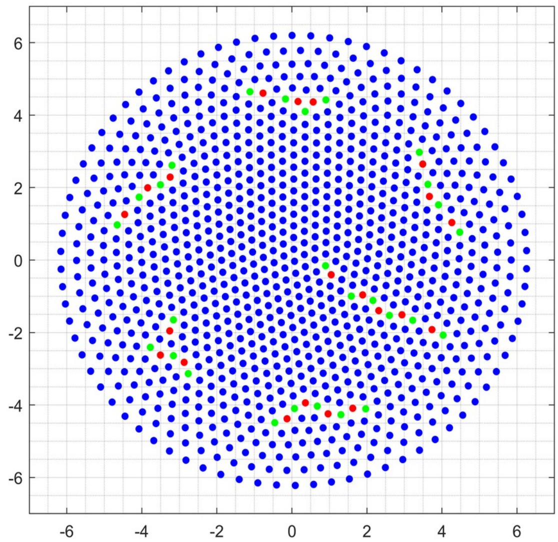

Figure 1. An ordered structure of the ensemble of spinners forms chains of defects, with the total number of spinners in the ensemble is N=1027.

References

[1] B. Shinde, R. Livanovičs, and A. Cēbers, *JMMM* 567, 171314 (2023).

Orientational order of the hexagonal distribution of an ensemble of spinners

Andrejs Tatuļčenkovs, Bhagyashri Shinde, Andrejs Cēbers
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The dynamics of rotating spinners in a two-dimensional geometry are studied. The motion of the spinners is driven by an external torque that imparts rotational movement to the spinners (particles) [1]. Considering the hydrodynamic interactions between the spinners, the collective motion of the spinner ensemble emerges. Using numerical simulations, the nonlinear dynamics of the spinner ensemble, including the formation of defects [2] in the hexagonal lattice of the spinners, are investigated. The behavior of the hexagonal orientational order parameter within the spinner ensemble is also analyzed (Fig.1).

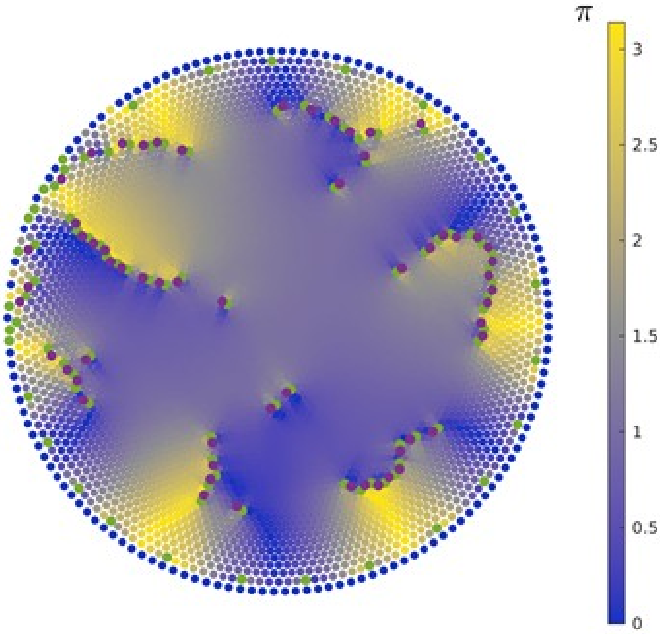

Figure 1. Phase of hexagonal orientational order parameter (N particle = 3000).

References

[1] B. Shinde, R. Livanovičs, and A. Cēbers, *JMMM* 567, 171314 (2023).

[2] D. R. Nelson, *Defects and Geometry in Condensed Matter Physics*, Cambridge University Press (2002).

Numerical simulation of chevron pattern formation

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Labyrinthine pattern formed by the magnetic fluid in the plane layer under the action of the normal field have been studied since the beginning of 1980s [1]. The crucial issue concerning the understanding of the labyrinthine pattern formation is the concept of the renormalization by the long-range magnetic interaction forces of surface tension. This effective surface tension reaches exactly zero value for the case of equilibrium stripe structure [2,3], and the quasi-stacionary evolution of stripe patterns is governed by the curvature elasticity of pattern, thus the pattern behavior on a large scale is analogous to the behavior of the 2D smectic liquid crystals. Expansion of the magnetic fluid stripe pattern is caused by the increase of magnetic field since the period of equilibrium pattern decreases with the strength of magnetic field.
The numerical studies of the instabilities of magnetic stripe patterns for the first time were done for concentration patterns in ferrocolloids [4]. The collective behaviour of magnetic fluid patterns is studied numerically in [5]. There the numerical simulation results concerning the chevron pattern evolution from the lattice of separate droplets is presented. The values of critical parameters for undulation and hairpin stability are compared with theoretical predictions [2,3].
In presented calculations the droplets of magnetic fluid initially is arranged in hexagonal lattice. The size of droplets is denoted by desired magnetic fluid volume fraction in pattern 0.3. To obtain correlated elongation and to produce straight stripe pattern all droplets are slightly elongated in y-direction. Numerical experiments where performed using linearly with time increasing magnetic Bond number $Bm=2M^2\ h/\sigma$ with various increase rates, where M-magnetization of droplet, h-thickness of cell and σ-magnetic fluid surface tension. Obtained stripe patterns exhibit undulation instability leading to the formation of chevron pattern. Some examples of pattern evolution is presented in figure below.

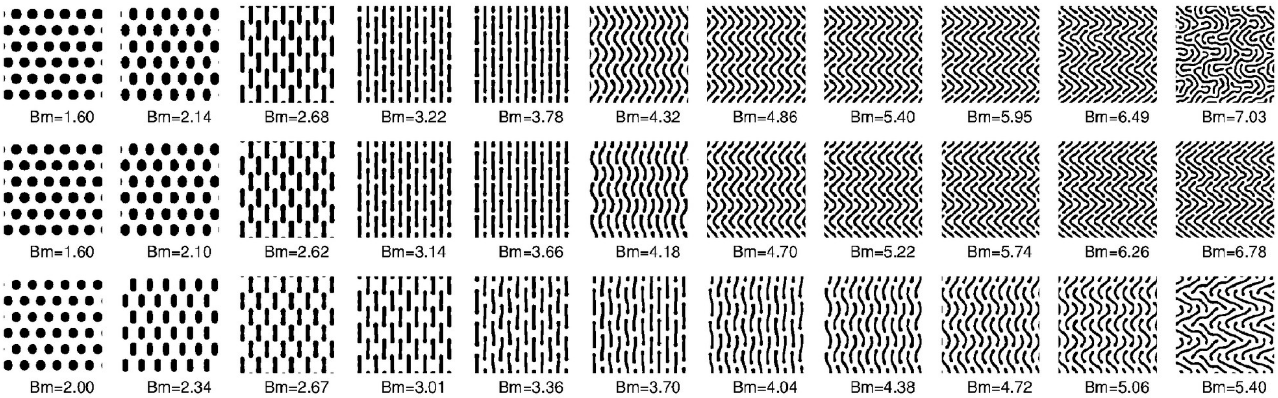

Figure 1. Examples of pattern evolution.

References

[1] A. Cēbers and M. M. Maiorov, *Magnetohydrodynamics* 16, 231 (1980).
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[3] A. Cēbers, *J. Magn. Magn. Mater.* 149, 93 (1995).
[4] A. Cēbers, *Phys. Rev. E* 61, 700 (2000).
[5] I. Drikis, J.-C. Bacri, and A. Cēbers, *Magnetohydrodynamics* 35, 203 (1999).

Macroscopic experiments of magnetic particle dynamics

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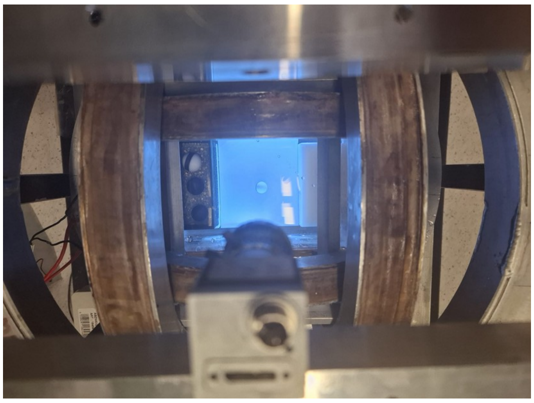
The study explores the three-dimensional rotation of magnetic particles in a viscous medium under a rotating magnetic field [1]. The research focuses on determining critical angular frequency transitions from synchronous to asynchronous motion, identifying the separatrix [2], and analyzing inertial effects. Using a Helmholtz coil system for magnetic field generation, the experiment involves a neodymium magnet encased in a PLA sphere, tracked by a Basler camera (Fig.1). The results highlight dynamic behaviors below and above critical frequencies, providing insights into magnetic material dynamics with applications in bioengineering, microfluidics, and medical technologies like magnetic hyperthermia [3]. The experimental framework offers adaptability for modeling diverse magnetic systems.

a) 

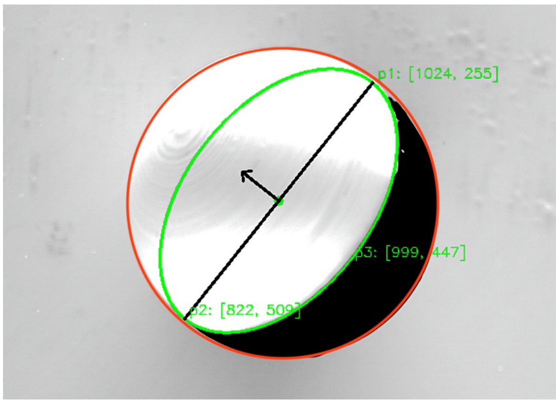
b) 

Figure 1. a) Experimental Apparatus; b) Magnetic Moment Vector Determination.

References

[1] A. Cēbers, *Magnetic Soft Matter Fundamentals and Applications*, RSC (2023).
[2] V. Palkar et al., *Phys. Rev. E* 100, 051101 (2019).
[3] M. Szwed and A. Marczak, *Cancers* 16, 1156 (2024).

Life in microfluidics: our results and outlook

Viesturs Sints
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Microphysiological devices aim to replicate human organ functionality in microfluidic systems. The success of such approach would rely on understanding and replicating the complex rheological properties of the fluids encountered in physiological systems. We have developed methods to experimentally investigate and describe flow within Organ-on-a-chip (OOC) devices. Our research has revealed non-Newtonian properties of the fluids that haven't been properly accounted for by the research community. Further application of the competencies available to us could see a closer integration with cell cultivation research and the introduction of magnetic materials to OOC systems.

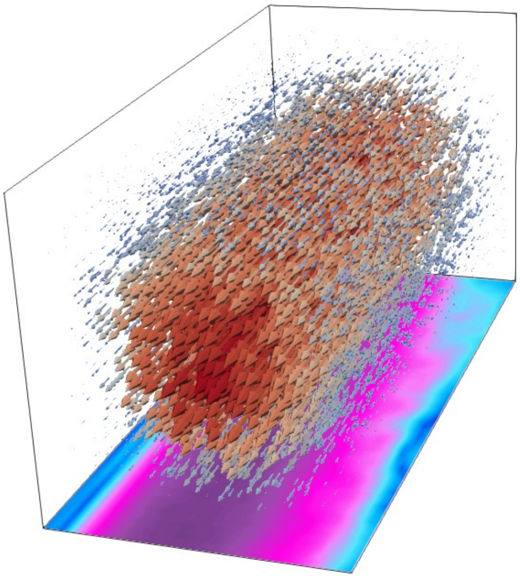

Figure 1. Flow and shear stress in a channel of an Organ-on-a-chip device

Some physical-chemical characteristics of the magnetic electrospun materials based on polyacrylonitrile (PAN)

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Polymer fibers attract much attention due to their unique features, such as biocompatibility and broad flexibility. Imparting magnetic properties to the fibers allows expanding the range of applications [1]. The synergy between the two classes of materials by tuning the properties of the resulting magnetic fibers can make them suitable for magnetic soft matter applications.

This work reports about research that aims to explore how different types of maghemite (γ-Fe_2O_3) magnetic nanoparticles' (MNPs) coating influence the properties of polyacrylonitrile (PAN)-based fibers obtained by the electrospinning method. The obtained spun materials were characterized by optical and scanning electron microscopy, exploring morphological properties of the fibers. MNPs distributions in the spun fibers were measured by SEM-EDX. Magnetic characteristics of the obtained materials were characterized using VSM.

It has been found that for the fabrication of PAN-based magnetic spun materials most suitable MNPs (γ-Fe_2O_3/ac) are those with the positive charge on the surface. This material exhibits magnetic properties similar to those of the applied ferrofluid (see Fig. 1: SpM1). The uniform longitudinal distribution of the magnetic nanoparticles inside the PAN-based nanofibers was found. The SpM1 sample depicted the highest incorporation of the maghemite NPs in the nanofibers (88.4% of the total number of particles involved in the spinning process) [2].

Figure 1. SEM images of the samples of magnetic PAN-based materials. The SpM1: γ-Fe_2O_3/ac nanofibers the average diameter is 0.5 ± 0.1 μm (scale bar 5 μm**).** SpM2 (γ-Fe_2O_3/citr) nanofibers the average diameter is 0.2 ± 0.1 μm; the average spindle-like formation on the fibers diameter is 0.8 ± 0.2 μm (scale bar 10 μm). SpM3 (γ-Fe_2O_3/citr/dextr) nanofibers the average diameter is 0.2 ± 0.1 μm; the average spindle-like formation diameter is 0.6 ± 0.1 μm (scale bar 5μm).

References

[1] L. M. Gradinaru et al., *Polymer* 256, 125186 (2022).
[2] O. Petrichenko et al., *Proc. 13th PAMIR Int. Conf. Fundamental and Applied MHD*, Carry-le-Rouet, France, 125 (2024).

Explicit and fully automatic analysis of magnetotacticbacteria motion reveals the magnitude and length scaling of magnetic moments

Māra Šmite[1], Mihails Birjukovs[1], Pēteris Zvejnieks[2], Ivars Driķis[1], Guntars Kitenbergs[1], Andrejs Cēbers[1]
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[2]Department of Physics, University of Latvia

Magnetotactic bacteria (MTB) are a diverse class of microorganisms whose motility can be controlled using an external magnetic field, which is relevant for applications in medicine and microfluidics. A fundamental property of MTB is their magnetic moment **m**, which is challenging to measure experimentally. We introduce an explicit, fully automated method to calculate **m** from the trajectories of MTB using the established U-turn method [1]. Unlike the conventional U-turn time-based method, our approach is based on a theoretical U-turn shape function. This method directly incorporates the geometry of the U-turn and determines **m** from the width of the U-turn branches. We integrate this with a robust U-turn decomposition algorithm capable of detecting U-turns from bacterial tracks independent of their orientations. Our results [2] reveal a linear relationship between magnetic moment and the size of the bacteria. Additionally, we demonstrate that the proposed U-turn shape-based method yields significantly different results compared to the traditional time-based approach (Fig. 1.)

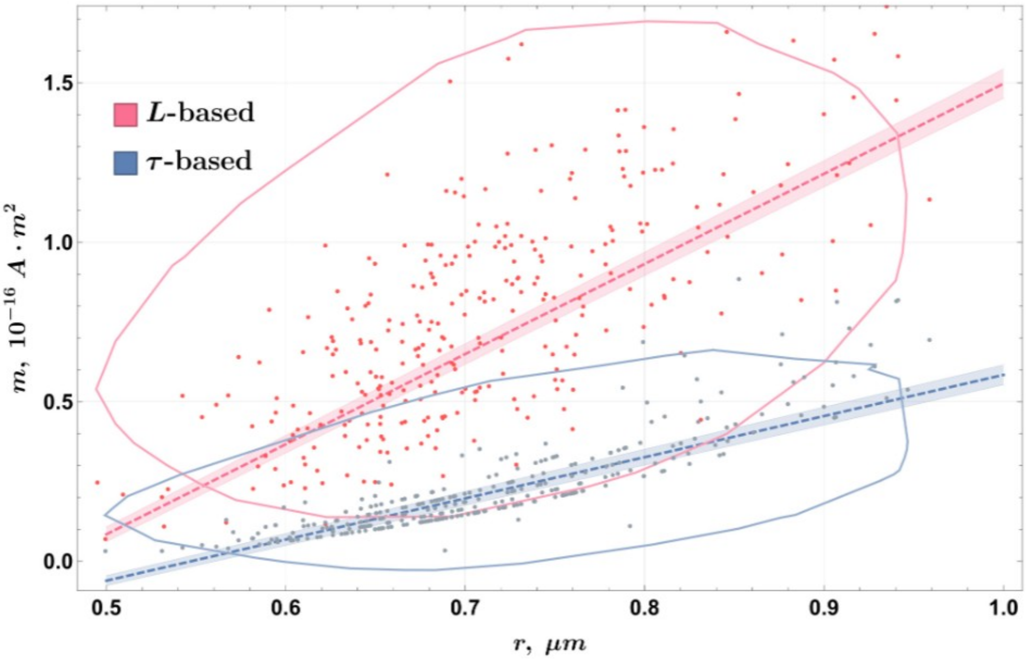

Figure 1. Magnetic moment value calculation, calculated based on time τ and distance between U-turn branches L.

References

[1] S. Esquivel, D. M., and De Barros, *Exp. Biol.* 121, 153–163 (1986).
[2] M. Šmite et al., arXiv:2501.09869 (2025).

Gyromagnetic effects in the dynamics of a levitating magnetic particle

Rūdolfs Livanovičs, Andrejs Cēbers
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We consider the oscillatory dynamics of a small spherical magnetic particle suspended in levitation above a superconductor. The particle is initially forced to rotate, a process which continues largely unabated due to minimal rotational drag and therefore negligible dissipation. When gyromagnetic effects are taken into account, and the corresponding Einstein frequency is non-zero, the particle enters a regime of periodic nutation oscillations [1], the period of which can be established theoretically and verified numerically. Analysis of the Fourier spectrum of the oscillations reveals two distinct frequencies, the higher of which corresponds to the expected precession of the particle. The lower frequency, which has also been observed experimentally, appears to result from the particle shifting back and forth across the y axis. We find that the values of the two frequencies are related, in that the lower frequency scales linearly with the inverse of the higher precession frequency across a wide range of values of the Einstein frequency.

References

[1] M. Belovs, R. Livanovičs, and A. Cēbers, *JMMM* 172735 (2024).

Recent results on gravity stabilized magnetic micro-convection

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Magnetic micro-convection is an instability occurring at the interface between miscible magnetic and non-magnetic fluids, driven by an external magnetic field [1]. In this study, we experimentally and numerically investigate the influence of gravity, initial interface smearing, and other key parameters on the dynamics and mixing efficiency of magnetic micro-convection in a vertical microfluidic chip (see Fig.1.).

Using Hele-Shaw cell-like microfluidic setup, we systematically varied critical parameters, including the thickness of the pre-mixed fluid layer, the intensity of the applied magnetic field, the density differences between the fluids (achieved by using magnetic fluids of varying concentrations), and the thickness of the microchannels. Dimensionless parameters—magnetic and gravitational Rayleigh numbers [2]—were employed to quantify the interplay of forces.

The study successfully observed magnetic micro-convection in initially stagnant fluids, demonstrating that gravity restricts the mixing length [3]. This is shown experimentally, numerically and via linear stability analysis. Our results indicate that the critical magnetic field required for the onset of instability correlates with initial interface smearing. We further investigate the relation between smearing and critical numbers and report the findings here. These results advance our understanding of this complex phenomenon and give ideas for its more general interpretation.

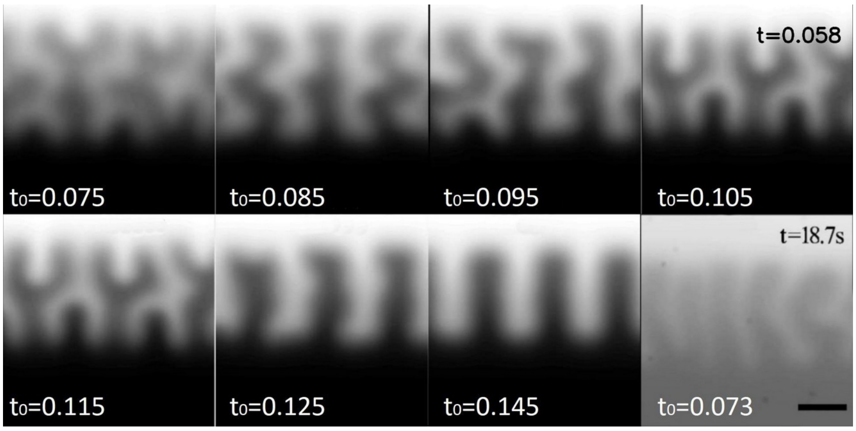

Figure 1. Magnetic micro-convection development for various initial smearing parameters t_0 at 19 seconds since the beginning of the experiment. Comparison between numerical simulations and experiment (lower right frame). The scale bar is 0.1 mm long.

References

[1] A. Cēbers and M. M. Maiorov, *Magnetohydrodynamics* 16, 21 (1980).
[2] G. Kitenbergs et al., *Eur. Phys. J. E* 41, 138 (2018).
[3] L. Puķina-Slava et al., arXiv:2310.15323 (2023).

Engineering tunable fractional Shapiro steps in colloidal transport

Andris P. Stikuts[1], Seemant Mishra[3], Artem Ryabov[2], Philipp Maass[3], Pietro Tierno[1]
1. University of Barcelona, Department of Condensed Matter Physics
2. Charles University, Department of Macromolecular Physics
3. University of Osnabrück

Shapiro steps are quantized plateaus that appear in current-voltage or velocity-force characteristics in various oscillatory driven systems, which have an internal periodicity. They were first observed in 1963 by S. Shapiro [1], who was driving a superconductor Josephson junction using a microwave signal. Later such steps have been seen in many systems, both quantum and classical [2]. We show experimentally and theoretically how, in addition to integer Shapiro steps, where the plateaus are an integer multiple n apart from the smallest one, we also obtain fractional Shapiro steps, where the plateaus are a rational fraction p/q multiples of the smallest one. In the experiment, a colloidal bead is driven across a potential created by optical tweezers. We engineer the optical landscape in such a way that the bead displays fractional and/or integer Shapiro steps in its average velocity. We use the easily observable length and time scales of the colloidal particle's motion to visualize and elucidate the mechanisms for the appearance of these steps.

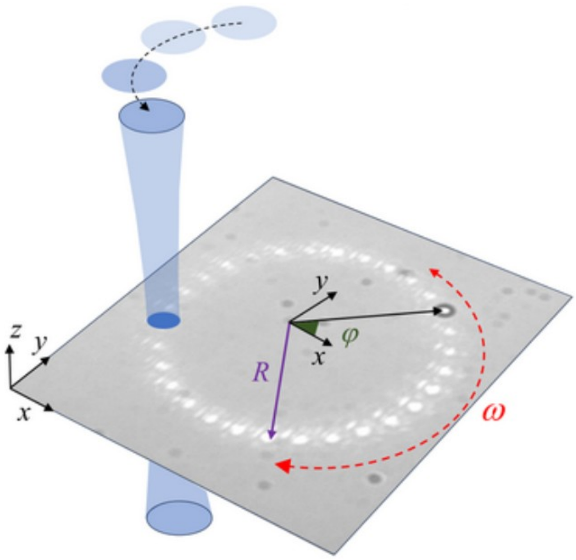

Figure 1. Schematic of a micro-bead (dark ring) driven over a landscape of optical traps (white spots).

References

[1] S. Shapiro, *Phys. Rev. Lett.* 11, 80 (1963).
[2] M. P. Juniper et al., *Nat. Commun.* 6, 7187 (2015).

Magneto-Optical Sensing of Superparamagnetic Iron Oxide Nanoparticles in Aqueous Solution

Ethan To[1], Aleksander Zosuls[1], In Young Park[1], Joyce Y. Wong[1,2]

Department of Biomedical Engineering, Boston University[1]
Department of Materials Science and Engineering, Boston University[2]

The magneto-mechanical actuation of superparamagnetic iron oxide nanoparticles (SPIONs) under dynamic magnetic fields has gained great attention due to its versatile applications in biosensing, microrheology, tissue engineering, and drug delivery [1]. SPIONs exhibit a large and reversible magnetic response, meaning they will strongly respond and rotate to align their magnetic moment with the direction of an external magnetic field (MF), however, will have no net magnetization when the MF is removed. If multiple SPIONs are in proximity to each other when exposed to an external MF, they will assemble in a head-to-tail fashion to form chain-like assemblies that behave as larger magnetic agglomerates [2, 3]. In the present study, we focus on the design and construction of a low frequency dynamic magnetic field device capable of producing magnetic field strengths up to 200 Oe at frequencies between 1-100 Hz. We demonstrate aggregation and rotation of SPIONs in water and viscous solution observed via optical spectrophotometry. The percentage of transmitted light through a polystyrene cuvette filled with 1 mg/mL SPIONs in deionized water or 80% glycerol/water solution subjected to static or dynamic MF treatment was measured via OceanOptics USB2000+ spectrometer. Overall, this study demonstrates a method for characterizing the magneto-mechanical actuation of SPIONs by measuring variations in transmitted light intensity. Future investigation will focus on leveraging the magneto-mechanical actuation of SPIONs exposed to dynamic MFs to disrupt biological structures such as the fibrin matrix found during the formation of surgical adhesions.

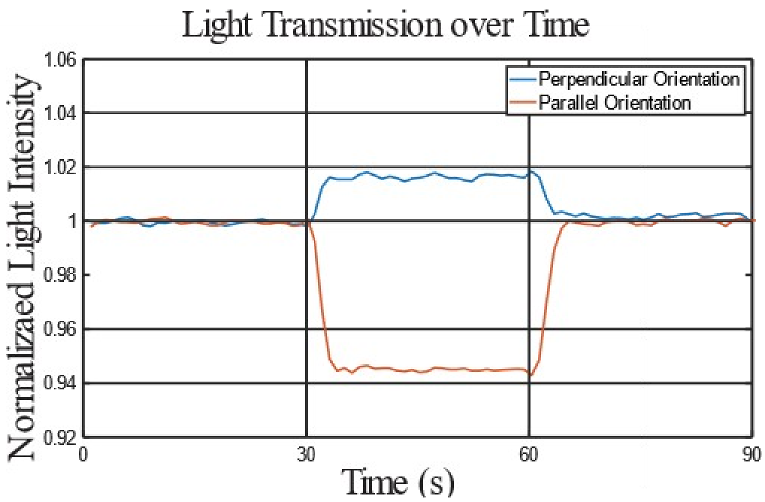

Figure 1. Normalized light intensity over time under a 50 Oe static magnetic field in various orientations. The magnetic field is turned on at 30 s and turned off at 60 s.

References

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About

The main organization of this section is done by the MMML lab (Lab of Magnetic Soft Materials) of the University of Latvia. More information about our activities and research interests can be found on our website https://mmml.lu.lv.

Section chair is Dr. Jorge Luiz Coelho Domingos.

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FUNDAMENTAL AND APPLIED RESEARCH PROJECTS

Funded by the European Union