Computer simulations of magnetocapillary swimmers

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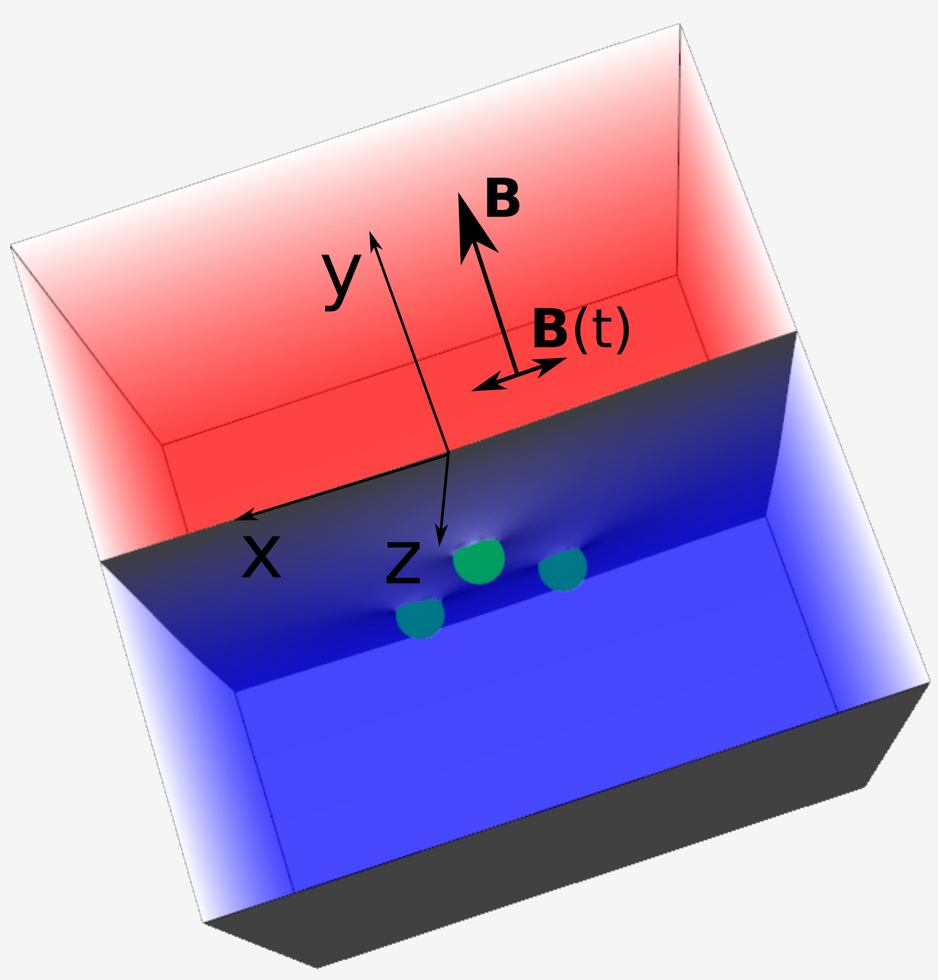
I. Introduction

Self-assembled magnetocapillary microswimmers were experimentally demonstrated recently [1]. When three magnetic particles are placed at a fluid-fluid interface, the particles deform the interface due to their weights, leading to capillary attraction. If a static magnetic field is applied perpendicularly to the interface, the particles experience a repulsive magnetic dipole-dipole interaction. Through the competition of attractive capillary and repulsive magnetic forces, a stable assembly of the three magnetic particles is achieved. By applying an additional oscillating magnetic field, the particle assembly demonstrates a directed motion. Here, we numerically study the effect of *frequency* and *direction* of the magnetic field on the motion of the swimmer and demonstrate the possibility to utilize the swimmer for transporting *cargo particles*.

II. Methods and simulation setup

For the simulation of fluids we apply a hybrid lattice Boltzmann method (LBM) [2]. Multiple components are calculated locally according to the approach of Shan and Chen. Magnetic particles are discretized on the lattice and coupled to both fluid species by means of a modified bounce-back boundary condition [3, 4].



LBM parameters:

- Lattice units (l.u.): Δx, Δt
- Number of iterations: 2×10^6
- System: 128 x 128 x 128 l.u.
- Particle diameter D=10 l.u.
- Characteristic viscous time:

$$\tau_v = \frac{\rho_s D^2}{18 \rho_f \nu_s}$$

- Frequency of B(t) - field:

$$\frac{\omega}{2\pi} > \frac{1}{\tau_v}$$

[1] G. Lumay, N. Obara, F. Weyer, and N. Vanderwalle, Soft Matter **9**, 2420 (2013); G. Grosjean, G. Lagubeau, A. Darras, M. Hubert, G. Lumay, and N. Vanderwalle, Sci. Rep. **5**, 6035 (2015).

[2] F. Jansen and J. Harting, Phys. Rev. E **83**, 046707 (2011).

[3] Q. Xie, G.B. Davies, F. Günther and J. Harting, Soft Matter **11**, 3581 (2015); Q. Xie, G.B. Davies and J. Harting, Soft Matter **12**, 6566 (2016).

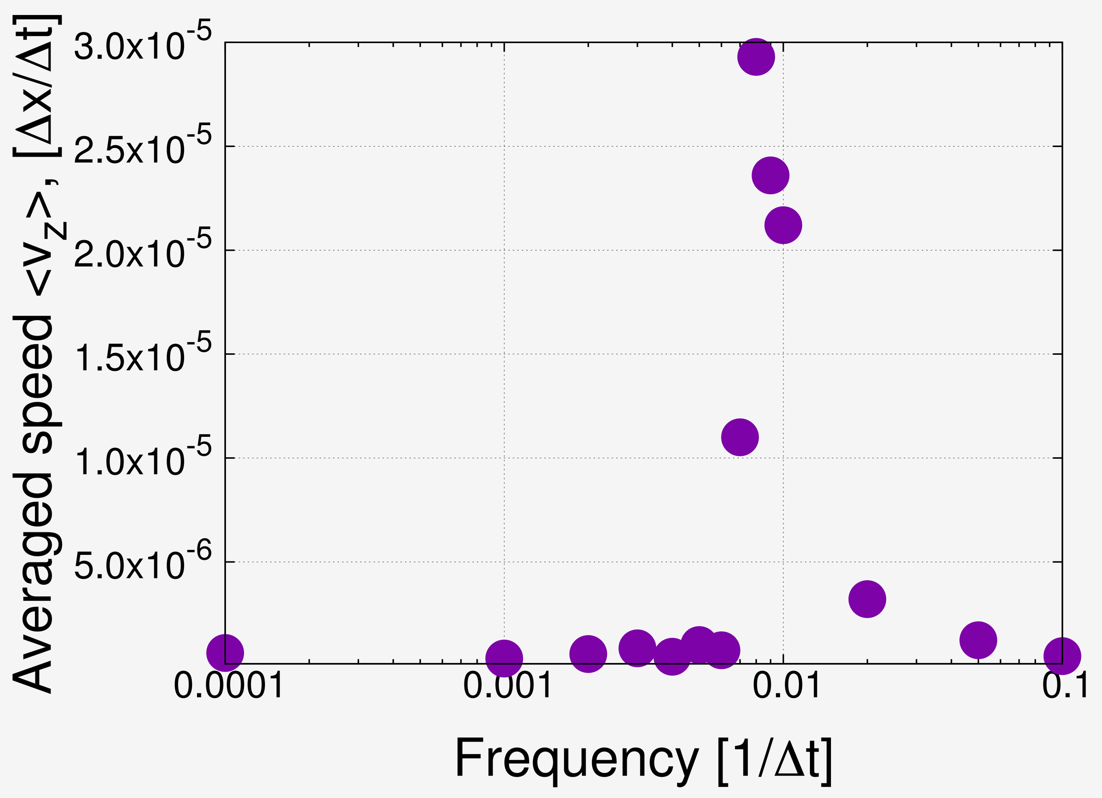
[4] G.B. Davies, T. Krüger, P.V. Coveney, J. Harting and F. Bresme, Adv. Mater. **26**, 6715 (2014).

[5] Q. Xie, A. Sukhov, J. Harting, in preparation.

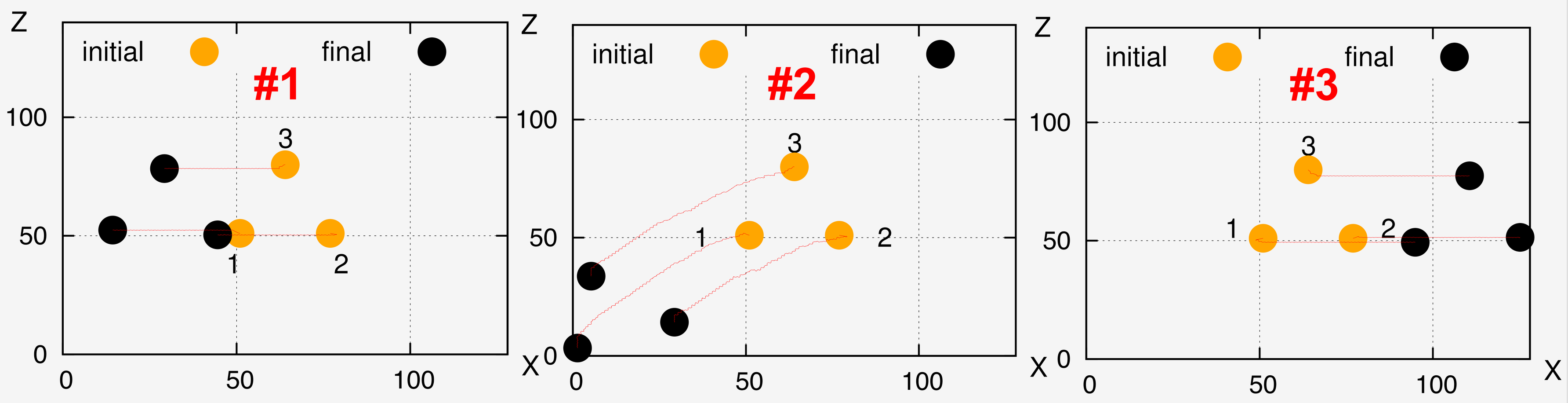
III. Numerical results

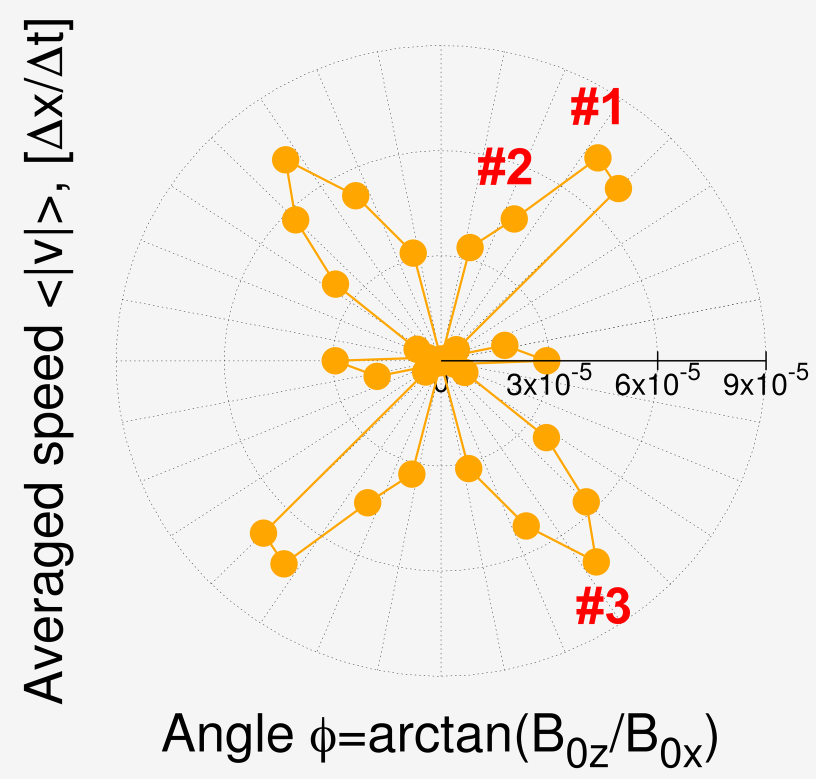
○ Frequency dependence of the average speed of swimmers

The average speed of the swimmer vs. frequency of the B(t)-field shows a resonant behavior for frequencies close to $1/\tau_v$.



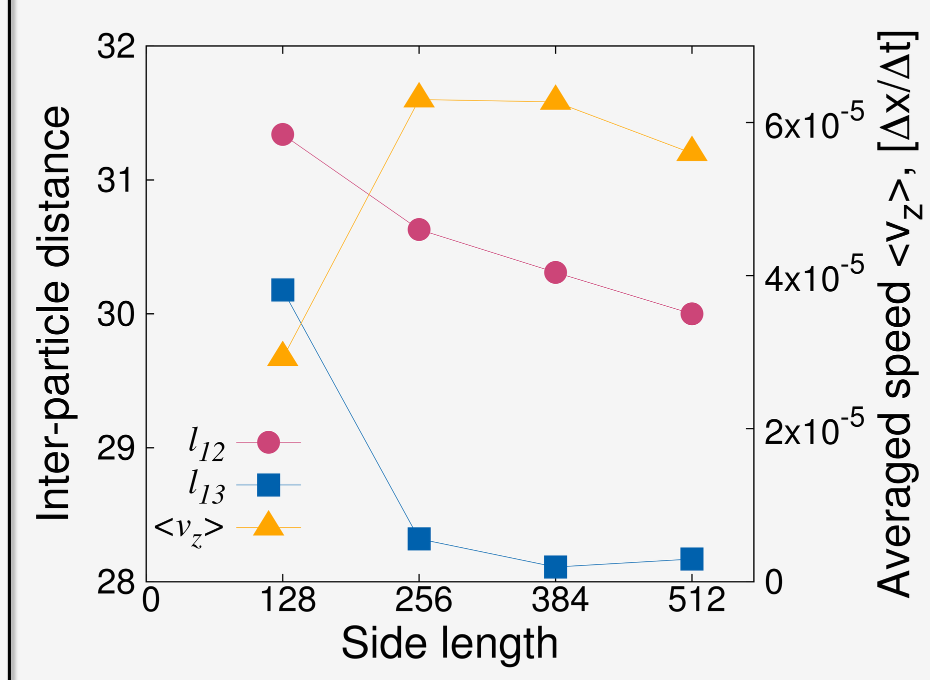
○ Influence of the direction of the oscillating magnetic field





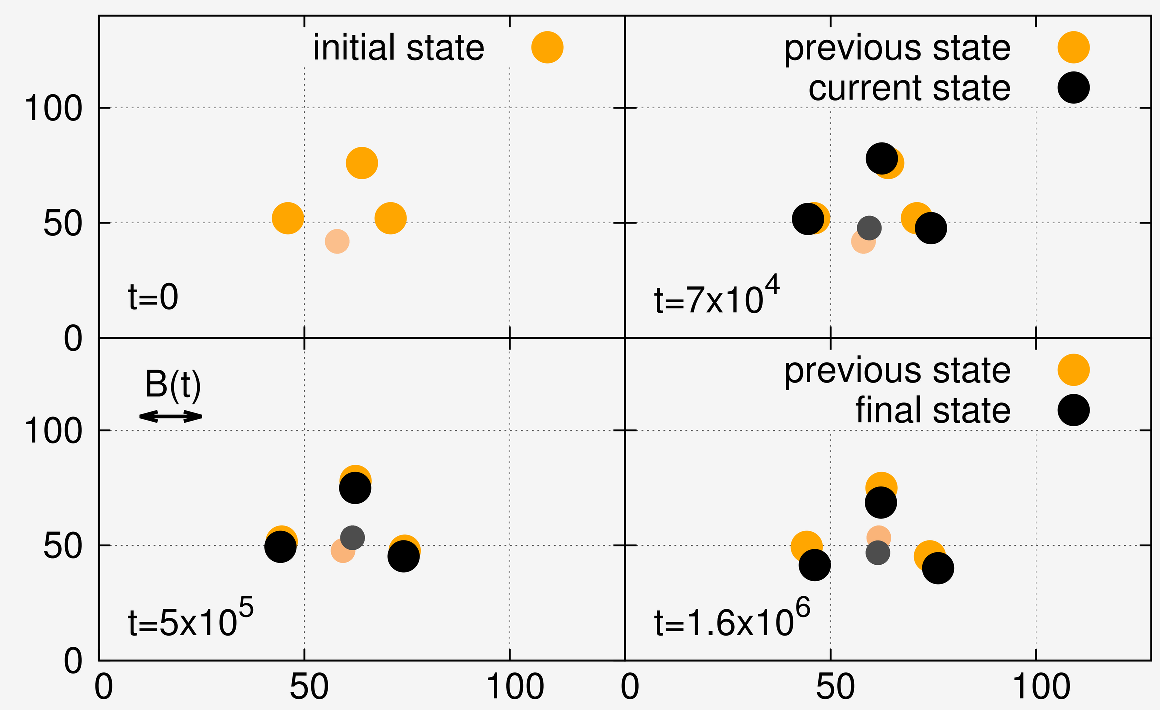
A directional dependence of both the averaged speed and velocity can be observed as a function of the B(t)-alignment.

○ Long range capillary interactions



Size of the simulation box influences the average speed of the swimmer.

○ Transporting cargo particles



A light *non-magnetic* particle can be captured and transported by the swimmer.