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Active ferrogranular matter: A robust dipolar dual-bead theory of ferrobot self-assembly and propagation

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Active ferrogranular matter is a paradigmatic platform for self-organization far from equilibrium[1]. We present a coarse-grained dipolar model that captures the self-assembly, propagation and hysteretic coarsening of so-called ferrobots [1, 2] –upright chains and 3D clusters of shaken steel spheres that autonomously wander, collide, merge and split under a vertical induction Bz. Each particle is a soft Lennard-Jones core carrying a virtual dipolar site rigidly bound to it [3]. N = 2137 spheres are confined in a box, periodic in x,y direction with a hard bottom wall in z, under gravity. We integrate a Langevin thermostat, dipolar coupling λ = 3.5 in ESPResSo, with long-range interactions.. The model robustly reproduces every diagnostic of the experiment. Structurally, a critical induction triggers Eiffel-tower-like clusters, consistent with an amplitude-equation analysis of a ferrogranular, active analog of the Rosensweig instability [4-6]; the cluster number density rises, peaks and decays linearly with coarsening, while the pattern wavenumber falls monotonically.

Hysteretically, the descending branch captures the reluctance of ferrobots to disintegrate, closing the same loop in cluster density and area fraction as measured. Kinetically, the velocity distribution stays isotropic and follows a stretched exponential with $\beta \approx 1.5$ [7], saturating at moderate fields. Diffusively, mean-squared displacements show a ballistic-to-diffusive crossover whose onset grows with Bz, mirroring the slowing-down of larger, stiffer ferrobots. The simultaneous reproduction of these five independent observables across the full hysteresis loop establishes the dipolar dual-bead model as a robust, predictive minimal framework for active ferrogranular matter.

References

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