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Floating surface potential of spherical dust grains in magnetized plasmas

Center of Excellence Ruhr-University Bochum PLASMA Science and Technology

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Introduction

Abstract

Plasma embedded dust grains getting charged because plasma particles hitting the grain surface and will be absorbed. Due to the larger mobility of electrons grains acquire a negativ floating charge. A dynamical equilibrium charge is reached when electron and ion current to the grain are equal. The charging currents are substantially changed if an external magnetic field is present because plasma particles motion becomes aligned with the field lines. In this work a particle-in-cell (PIC) simulation study of the charging of single, stationary and spherical grains in magnetized plasma environment is presented.

The numerical model

OPAR is a full 3D PIC code with a single, spherical dust grain in the center of a Cartesian grid system, see Fig. 1 (left panel). The sphere is treated as an inner boundary, plasma particles reaching the surface are removed from the simulation and their charge is accumulated to the floating charge Q_R. The points on the grain surface are set in every time step to the potential V_R. At the outer boundary particles can leave the system and new particles are injected to represent an infinite plasma medium outside the simulation box. The magnetized plasma is created by overlapping the box with a homogeneous and constant magnetic field in z-direction, see Fig. 1 (right panel).

Plasma parameters

The following plasma parameters were used in the simulations:

- Plasma density: $n_e = n_i = 6 \cdot 10^{15}/\text{m}^3$
- Temperature of electrons and ions: $kT_e = kT_i = 1\,\text{eV}$
- Plasma frequency of electrons: $\omega_e = 4.37 \cdot 10^9/\,\text{s}$
- Debye-length of electrons and ions: $\lambda_e = \lambda_i = 96\,\mu\text{m}$
- Grain radius: $R = 10,\ 20,\ 50,\ 100$ or $200\,\mu\text{m}$
- Most possible gyroradius of electrons: $r_{ge}^{mp} = 400$ to $0.01\,\mu\text{m}$
- Magnetic field strength: $B_z = 0.004$ to 169 T

In a Maxwellian plasma, the most possible gyroradius is

$$r_g^{mp} = \frac{m\,v_{mp}}{2eB_z} = \sqrt{\frac{m\,kT}{2}}\,\frac{1}{eB_z} \quad \text{with} \quad v_{mp} = \sqrt{\frac{2kT}{m}} \tag{1}$$

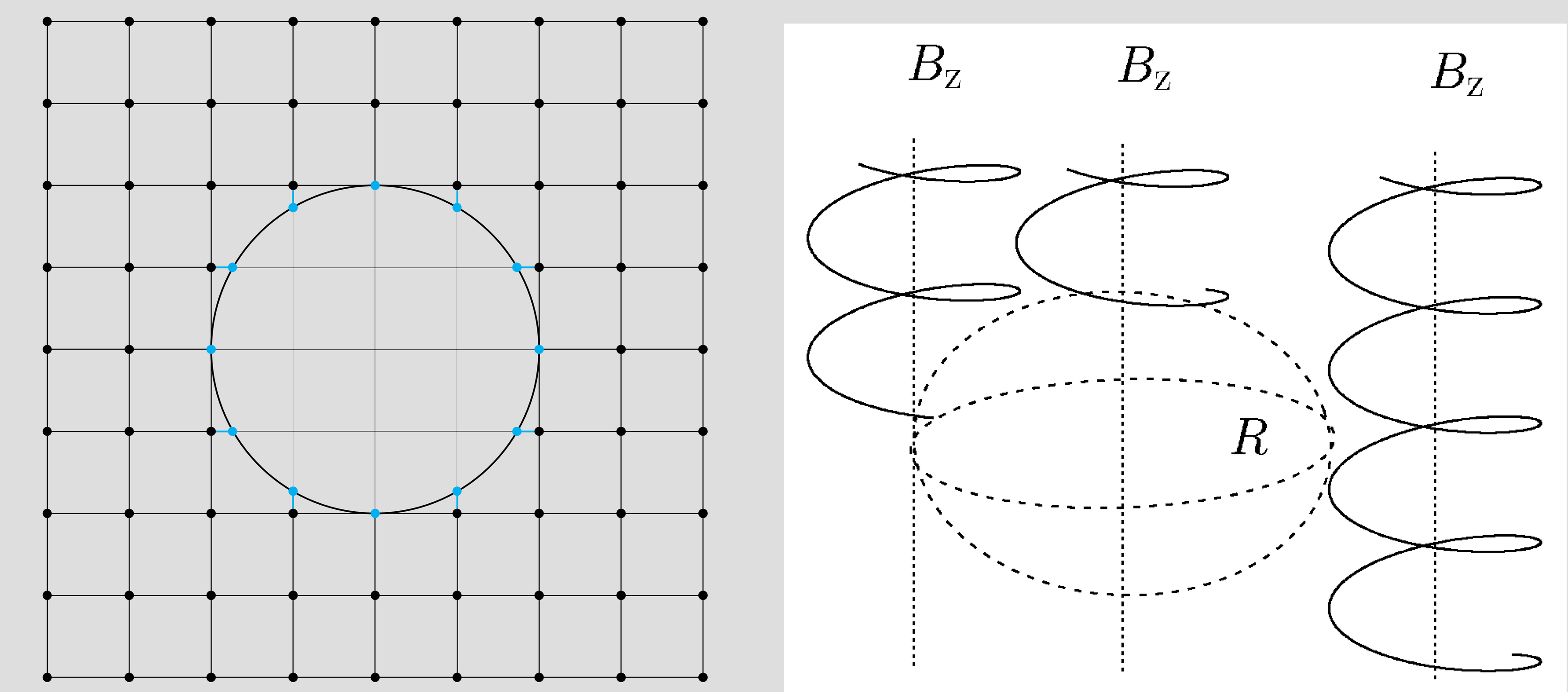

Figure 1: Left panel: A Cartesian grid system (for simplicity 2D) with a single, spherical dust grain in the center. The radius of the sphere is an integer multiple of the grid spacing Δx (here $R = 2\,\Delta x$). To reflect the spherical structure, the reduced grid point distances (blue lines) are considered in the Poisson solver. The (blue) points on the grain surface are set in every simulation time step to the surface potential V_R. Right panel: In a magnetic field B_z electron and ion trajectories are forced into spiral paths. The gyroradius follows by equating Lorentz and centripetal force, see (1).

Simulation results

Equilibrium surface potential

In Figure 2 (left panel) the time averaged surface potentials in equilibrium state for the five grains are shown for different gyroradiuses. With decreasing gyroradius (increasing B_z) the potentials become more negative for all grains. The significant change started when electrons gyroradius becomes considerably smaller than λ_e. For small ratios $\gamma_e = R/r_{ge}^{mp}$ the surface potentials tends for all grains to a modified OML theory for full magnetized charging currents [1]. The absolute value of the potential is not directly dependent on B_z, but on the ratio $\gamma_{e,i}$, which is shown in the right panel of Fig. 2. The surface potentials are not decreasing for $\gamma_i < 1 < \gamma_e$ in such a way which is predicted by a modified OML approach which considers a magnetized electron but unmagnetized ion charging current because electrons most possible gyroradius is always smaller than of ions a Maxwellian plasma [2]. For $\gamma_i > 1$ the potentials getting more negative and the absolute value becomes independent of the grain radius.

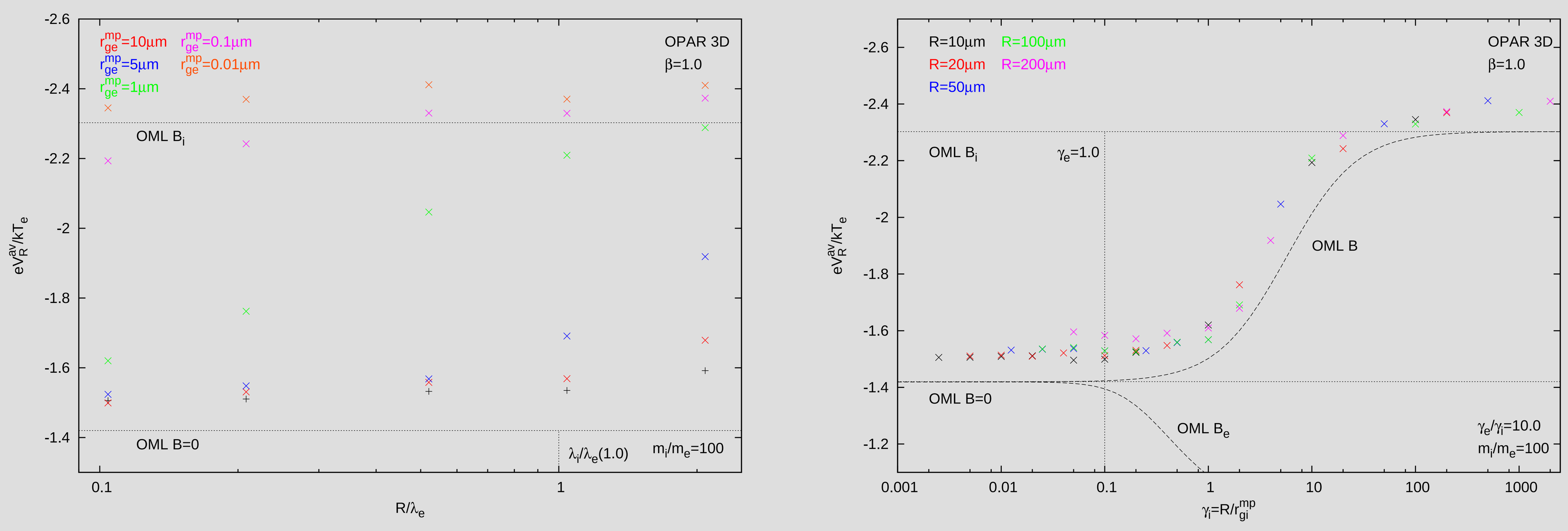

Figure 2: Time averaged surface potentials in equilibrium state for the five grain radiuses. The lower horizontal lines (OML $B = 0$) represent results from OML theory and the upper horizontal lines (OML B_i) from a modified OML for full magnetized charging currents [1]. Left panel: In dependence of R/λ_e for different r_{ge}^{mp}. The upright crosses are results of simulations without a magnetic field. Right panel: In dependence of $\gamma_i = R/r_{gi}^{mp}$. The dashed decreasing curve (OML B_e) represents a modified OML theory for magnetized electron but unmagnetized ion current [2]. The dashed increasing curve (OML B) models the transition between the none and full magnetized case.

Potential structure

The potential distribution around a grain in a strong magnetized plasma depends on the ratio R/λ_e, see Fig. 3. For the smallest considered grain radius (left panel) rotational symmetry remains nearly unchanged whereas for the largest grain (right panel) a negative potential profil in z-direction is formed because electrons with not sufficient energy to overcome the surface potential will be reflected backwards along B_z and every ion which is moving along a field line which penetrates the grain surface will be absorbed.

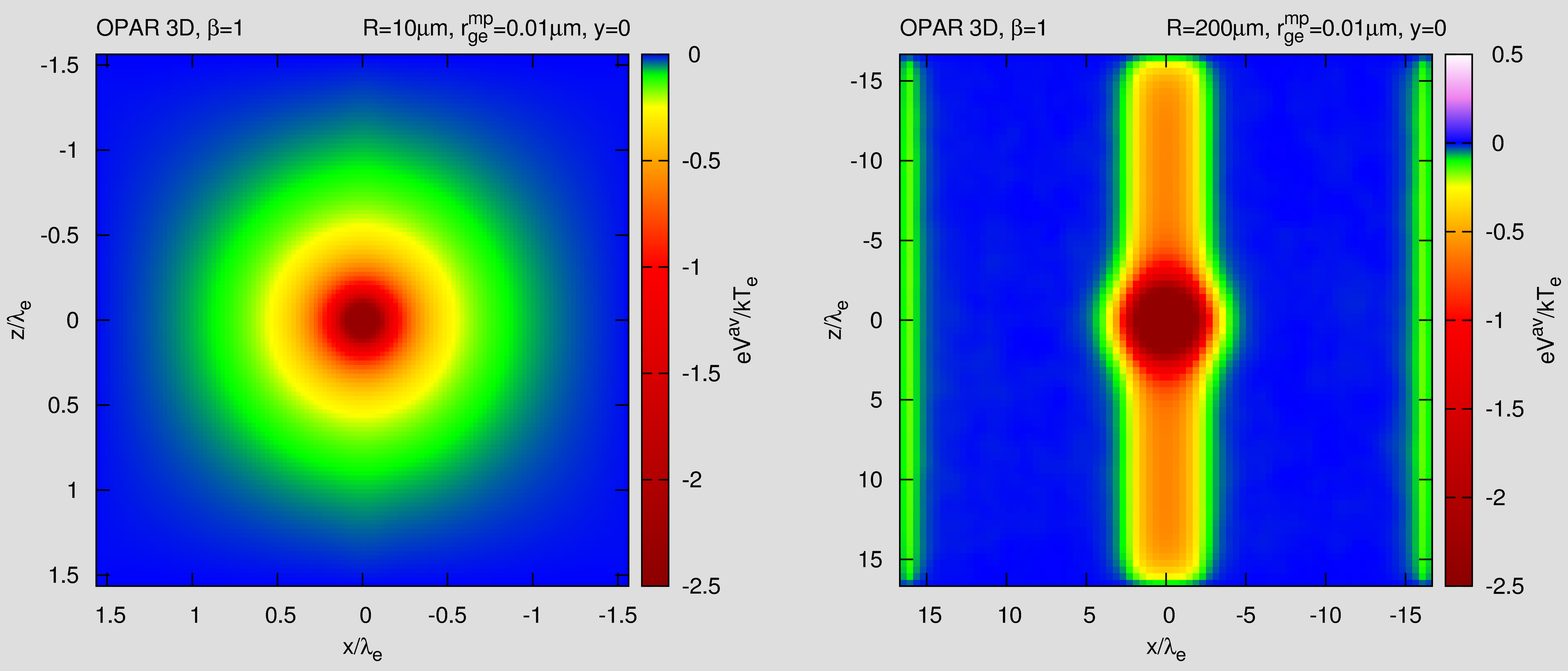

Figure 3: Time averaged potential distribution at equilibrium state in a central cross section (x-y plane) of the simulation box with the smallest grain radius (left panel, $R = 10\,\mu\text{m}$) and the largest (right panel, $R = 200\,\mu\text{m}$) in simulations with electron gyroradius of $r_{ge}^{mp} = 0.01\,\mu\text{m}$ (magnetic field in z-direction).

Conclusions

Although electrons are always stronger coupled to a magnetic field than ions in a Maxwellian plasma, a simultaneously situation of magnetized electron and unmagnetized ion charging current never exist. Due to the attractive potential, ions absorbing kinetic energy and its gyroradius strongly increases on the way to the grain by what ions with a certain phase angle of the spiral motion can miss the surface. This decrease of ions charging current is stronger than of electrons in a magnetized plasma for all grain radiuses.

Literature / Acknowledgments

[1] Tsytovich, V.N., Sato, N., Morfill, G.E. *Note on the charging and spinning of dust particles in complex plasmas in a strong magnetic field* New Journal of Physics (2003) vol. 5, pp. 43

[2] Patacchini, L., Hutchinson, I.H., Lapenta, G. *Electron collection by a negatively charged sphere in a collisionless magnetoplasma* Physics of Plasmas (2007) vol. 14, pp.062111

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