Dust Grain Potential in a Flowing Magnetized Plasma

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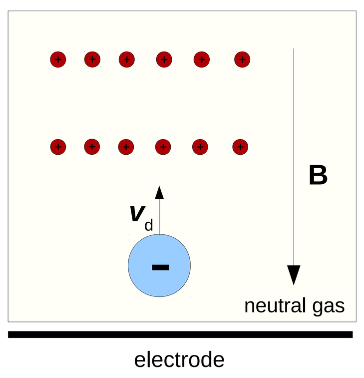
Motivation

- external magnetic field in direction of ion flow
- dielectric function approach accounts for finite ion temperature, ion-neutral collisions and the external magnetic field
- efficient calculation of the dust potential using 'Kielstream'
- shape of potential depends crucially on Mach number M
- for strong magnetization:
  - M<1: potential distribution is qualitatively different from the unmagnetized limit
  - M>1: magnetic field effectively suppresses the wake field

Dynamical Screening Approach

- linear response approach
- neutral gas at rest
- ions at rest
- dust particle moving with $\mathbf{v}_d = -\mathbf{v}_i$



$$\Phi(\mathbf{r},t) = \int \frac{d^3\mathbf{k}}{2\pi} \frac{q_d}{k^2} \frac{e^{i\mathbf{k}\cdot(\mathbf{r}-\mathbf{v}_d t)}}{\epsilon(\mathbf{k},\mathbf{k}\cdot\mathbf{v}_d)}$$

dynamically screened dust potential

$$\epsilon(\mathbf{k},\omega) = 1 + \frac{1}{k^2\lambda_{De}^2} + \frac{1}{k^2\lambda_{Di}^2}\left[\frac{1+\sum_{n=-\infty}^{\infty}\frac{\omega+i\tilde{\nu}_i}{\omega+i\tilde{\nu}_i-n\omega_{ci}}I_n(z)e^{-z}\xi_n Z(\xi_n)}{1+\sum_{n=-\infty}^{\infty}\frac{i\tilde{\nu}_i}{\omega+i\tilde{\nu}_i-n\omega_{ci}}I_n(z)e^{-z}\xi_n Z(\xi_n)}\right]$$

ω: $\mathbf{k}\cdot\mathbf{v}_d$

electrons: static screening

ions: dynamical screening → wake effects

substitution:

$$\xi_n = \frac{\omega - n\omega_{ci} + i\tilde{\nu}_i}{\sqrt{2}\,|k_z|\,v_{th,i}}$$

$$z = \frac{k_\perp^2 v_{th,i}^2}{\omega_{ci}^2}$$

ion cyclotron frequency:

$$\omega_{ci} = \frac{q_i B}{m_i}$$

thermal velocity:

$$v_{th,i} = \sqrt{\frac{k_B T_i}{m_i}}$$

plasma dispersion function:

$$Z(z) = i\sqrt{\pi}\omega(z)$$

$$\omega(z) = e^{-z^2}\mathrm{Erfc}(-iz) = \frac{i}{\pi}\int_{-\infty}^{\infty}\frac{e^{-t^2}}{z-t}dt$$

$I_n(z)$: modified Bessel function of the first kind

Set of dimensionless plasma parameters:

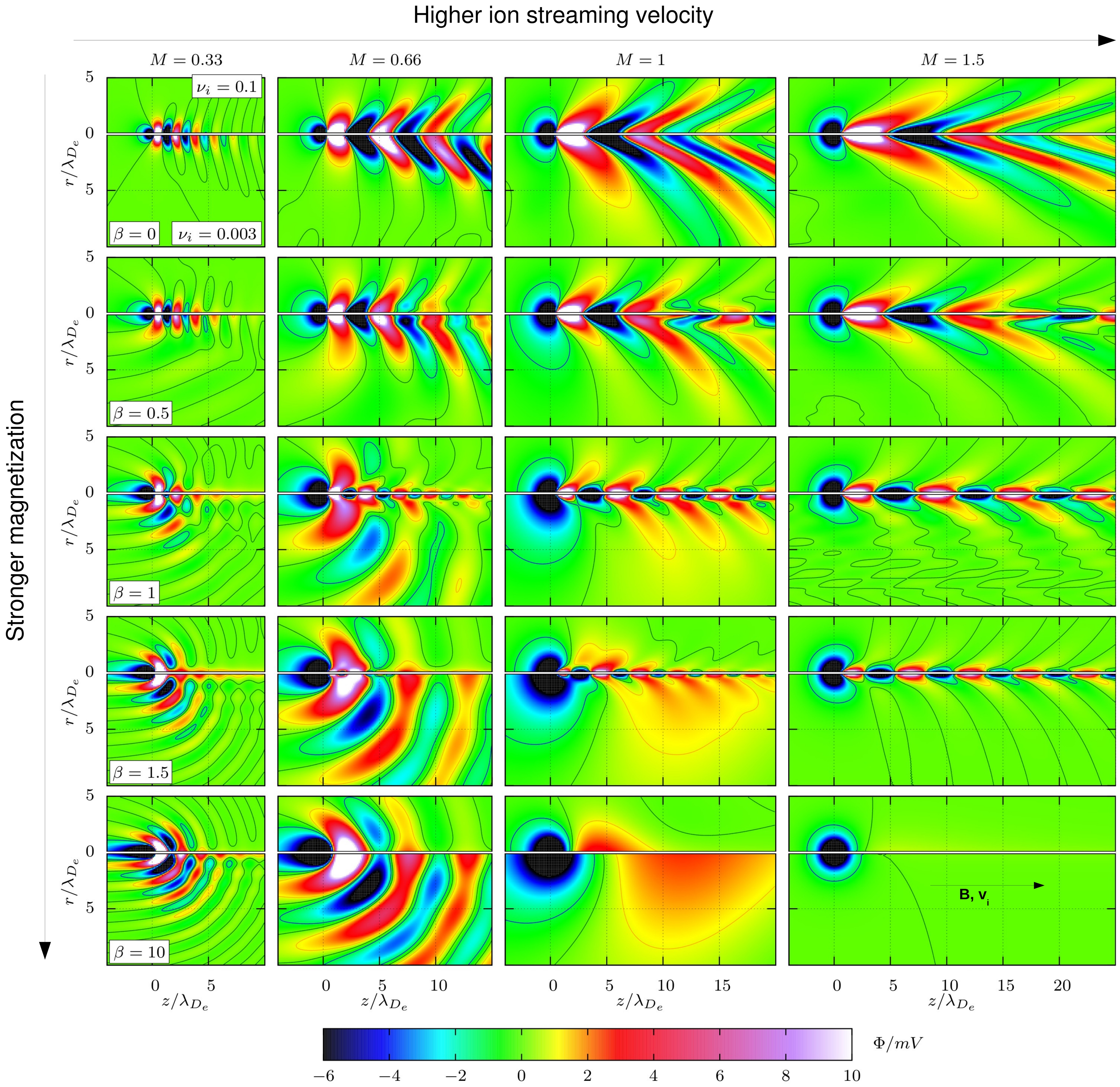
- Mach number $M = v_d/c_s$
- electron-to-ion temperature ratio $T_{ei} = T_e / T_i$
- ion-neutral scattering frequency $\nu_i = \tilde{\nu}_i / \omega_{pi}$
- magnetization $\beta = \omega_{ci}/\omega_{pi}$

ion sound speed:

$$c_s = \sqrt{\frac{k_B T_e}{m_i}}$$

used parameter:
λ_{De} = 845.2µm
T_{ei} = 100
q_d = 10000e

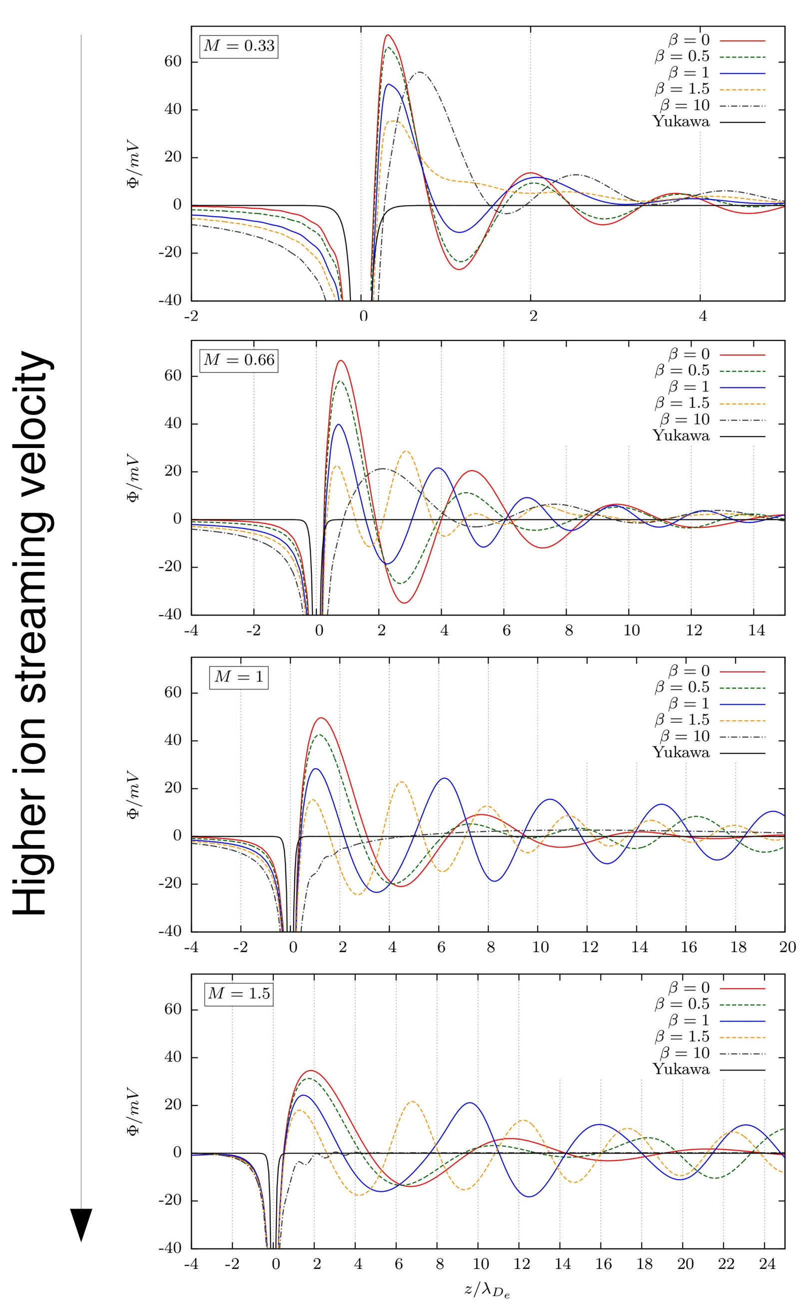
Dynamically Screened Grain Potential



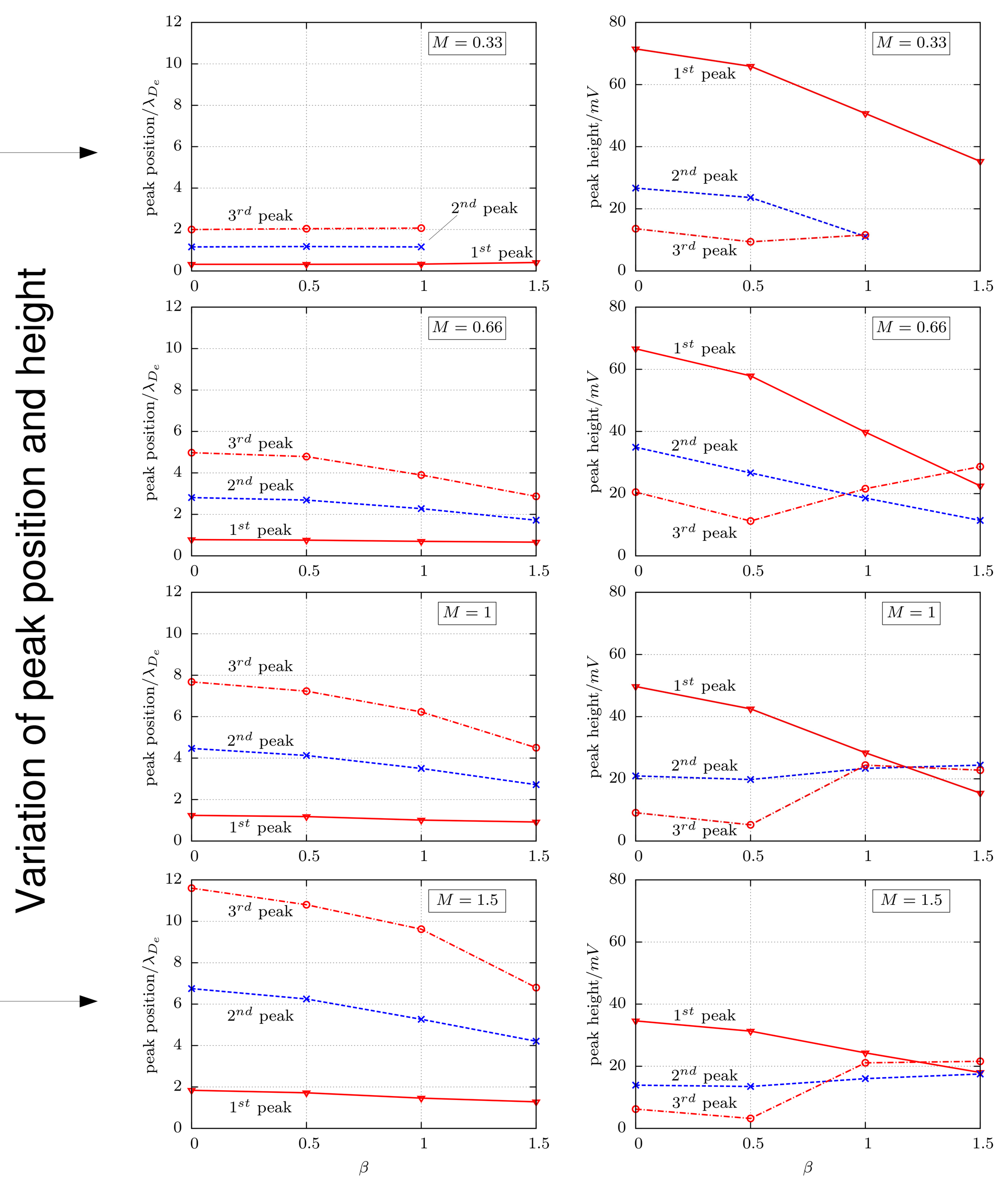
Contour plot of dust potential Φ(r) located at the origin with ions streaming from left to right and the magnetic field along the streaming direction for different values of the Mach number M and the magnetization β. From left to right: M = 0.33, 0.66, 1, 1.5. From top to bottom: β = 0, 0.5, 1, 1.5, 10. Upper half of each panel: finite damping (ν = 0.1), lower half: (almost) collisionless (ν = 0.003).

The shape of the potential crucially depends on the Mach number M. In the regime of subsonic ion flow, M<1, a strong magnetization even affects areas in front of the dust particle with additional potential peaks off the z-axis. For supersonic ion velocities, M>1, the magnetic field effectively suppresses the plasma wake field. Both effects are more pronounced for stronger magnetization.

Potential Along Magnetic Field/Streaming Axis



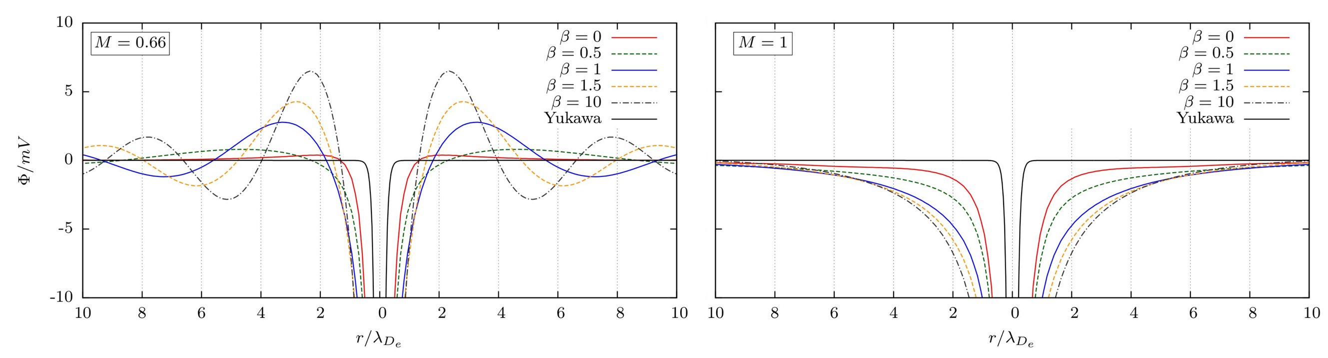
Potential cuts through the grain (r = 0) along the flow direction for different values of β and M = 0.33, 0.66, 1, 1.5 (from top to bottom). To find more pronounced effects the collision frequency is set to ν_i = 0.003.



Peak positions (left) and peak amplitude (right) along the flow direction for v_i = 0.003 and M = 0.33, 0.66, 1, 1.5 (from top to bottom) as a function of the magnetization β. Red (blue) curves correspond to a positive (negative) space charge.

For small magnetic fields, β < 1.5, the peaks shift toward the grain for increasing magnetization with the exception of M = 0.33, where the peak positions remain nearly constant. On the other hand, for β = 10 (see left panel), there is a significant difference between subsonic and supersonic ion velocity: For M < 1 the peaks shift away from the grain - contrary to the observations for small β. For M ≥ 1 the oscillations vanish completely.

Potential Perpendicular to Ion Flow



Potential cuts perpendicular to ion flow for z = 0, v_i = 0.003, M = 0.66 (left) and M = 1 (right).

For M = 0.66 the magnetization increases the oscillations of the wake potential, while for M = 1 the screening of the Coulomb potential is weakend.

Conclusion

- external magnetic field has strong impact on the grain potential
- this influence depends greatly on M and β
- wake potential becomes bent in upstream direction for subsonic ion speed (M<1) and is suppressed for supersonic ion speed (M>1)
- potential on z-axis changes dramatically for strong magnetization

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