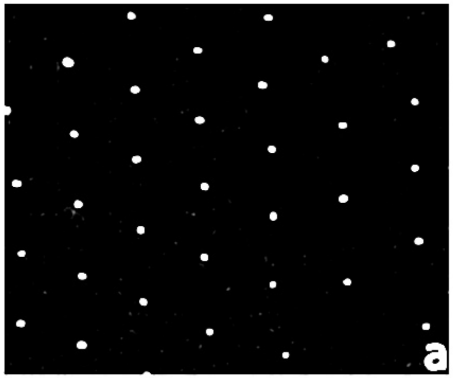
JIHT RAS

DYNAMICAL PROPERTIES OF THE CHAIN-LIKE STRUCTURE OF PARTICLES INTERACTING VIA NONRECIPROCAL QUASI DIPOL-DIPOL INTERACTION

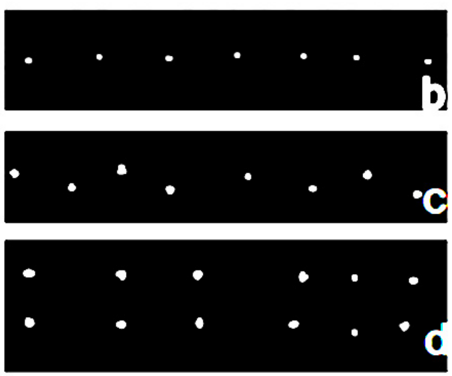
Irina I. Lisina, Olga S. Vaulina

KINETIC ENERGY REDISTRIBUTION FOR THE DUST PARTICLES IN THE LABORATORY EXPERIMENTS WITH RF-DISCHARGE PLASMA

Top view:



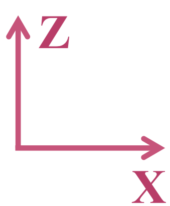
Side view:



[O. Petrov et al. 2011]

$$T_{dust} > T_e , T_i , T_n$$

Distribution of the Kinetic temperature	Z / X	Upper / Lower
J.B. Pieper, J. Goree, *PRL* (1996)	$T^Z / T^X < 1$	
A.K. Mukhopadhyay, J. Goree, *PRE* (2014)	$T^Z / T^X < 1$	$T^{UP} / T^{LOW} < 1$
A.A. Samarian, B.W. James, S.V. Vladimirov, and N.F. Cramer, *PRE* (2001)	$T^Z / T^X > 1$	
A. Aschinger, J. Winter, *NJP* (2012)	$T^Z / T^X > 1$	$T^{UP} / T^{LOW} < 1$
O.S. Vaulina, E.V. Vasilieva, O.F. Petrov and V.E. Fortov, *Phys. Scr.* (2011)	$T^Z / T^X > 1$	$T^{UP} / T^{LOW} < 1$
A.V. Ivlev, J. Bartnick, M. Heinen, C.-R. Du, V. Nosenko, and H. Löwen, *PRX* (2015)	$T^Z / T^X < 1$	$T^{UP} / T^{LOW} > 1$



THEORETICAL MODELS FOR HEATING

Microparticles can gain energy from the surrounding plasma

- if the charge spatially varies
  - [Zhakhovskii V.V., Molotkov V.I., et al. // JETP Lett.,1997]
  - [Zhdanov S.K., Ivlev A.V., Morfill G.E. // Phys. Plasmas, 2005]
- if the charge randomly varies with time
  - [R.A. Quinn and J. Goree // Phys. Rev. E, 2000]
  - [Vaulina O.S., Khrapak S.A, et al. // Phys. Rev. E., 1999]
  - [A.V. Ivlev, U. Konopka, G. Morfill // Phys. Rev. E, 2000]
  - [G. Norman, V. Stegailov, A. Timofeev // Contrib. Plasma Phys., 2010]
- if the electric field cause effect of delayed charging
  - [Nunomura S., Misawa T., et al. // Phys. Rev. Lett., 1999]
  - [Pustylnik M.Y., Ohno N., et al. // Phys. Rev. E, 2006]
  - [A.A. Samarian, B.W. James, et al. // Phys. Rev. E, 2001]

these theoretical models do not always allow us to explain the increase in kinetic energy (> 0.5 eV) for the dust particles for common conditions of laboratory experiments

THEORETICAL MODELS FOR HEATING

It was for the first time assumed in
[Schweigert V.A., et al. // PRL, 1996.]
that an increase in dust particles' energy
can be caused by an ion induced instability

The authors have also proposed a simple model of anisotropic pair interaction, which is similar to interaction occurs due to ion focusing

And numerically have shown that the location and density of the ion cloud is mainly depend on the position of the upstream particle and weakly depend on the position of the downstream one.

The simulation confirmed that this mechanism can provide both the conditions for alignment and a dramatic increase in the dust temperature.

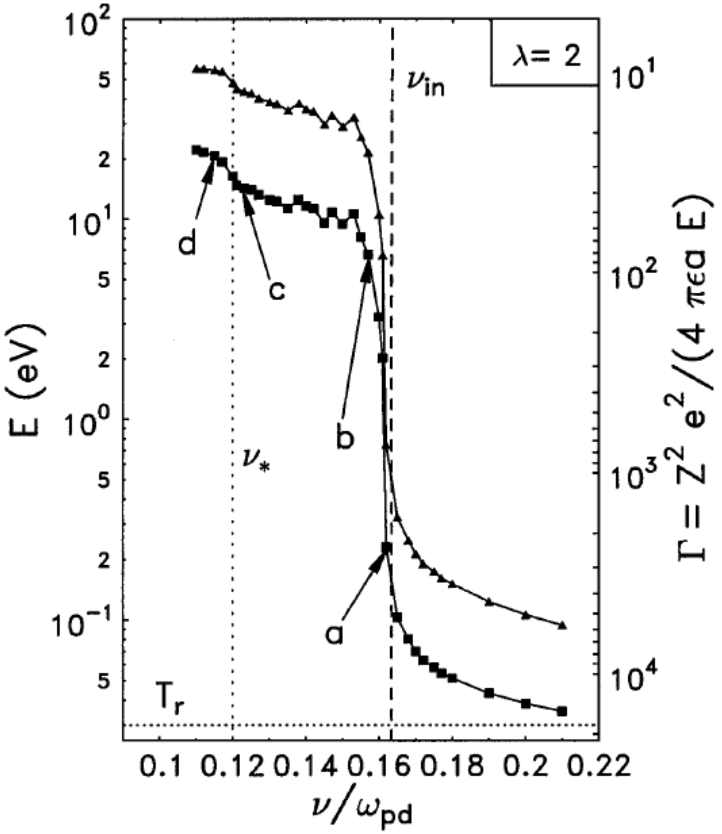


FIG. 3. The mean kinetic energy of the particles of the upper layer (squares) and the lower layer (triangles) for the Debye-Hückel interaction with $\lambda = 2$. The vertical dashed and dotted lines show the critical frictions corresponding to crystal instability ν_{in} and melting ν_*, respectively. The labels (*a*) to (*d*) refer to the trajectories in Fig. 2.

THEORETICAL MODELS FOR HEATING

Alignment and instability of dust crystals in plasmas

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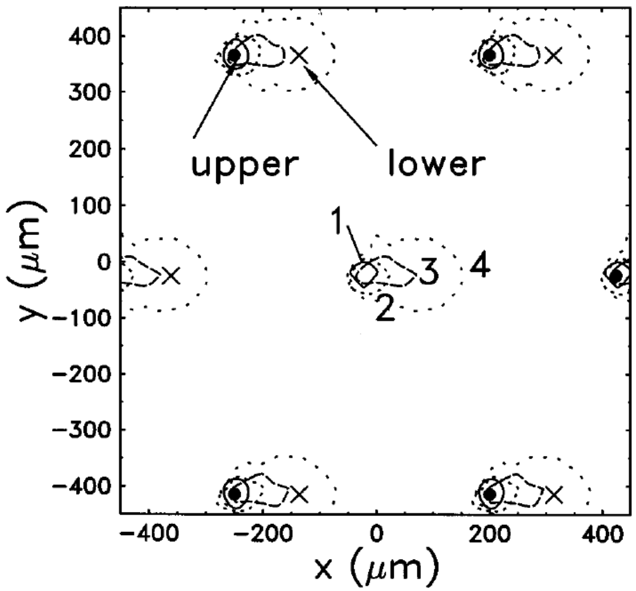
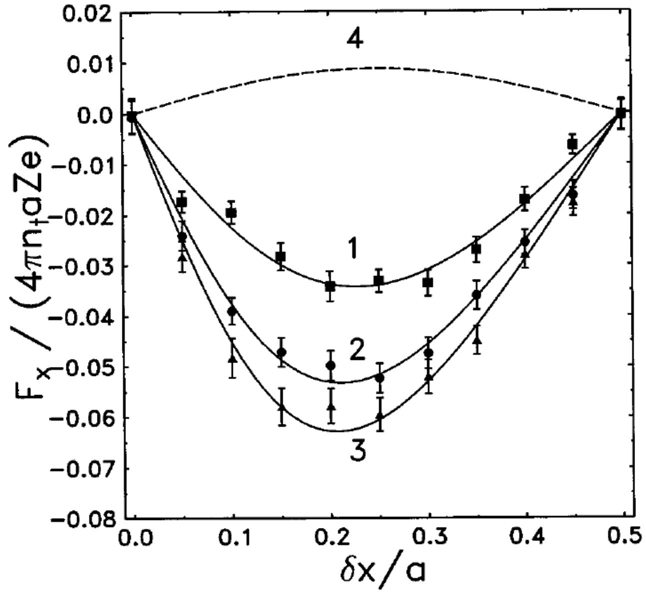
V. A. Schweigert,[1] I. V. Schweigert,[2] A. Melzer,[3] A. Homann,[3] and A. Piel[3]





that this restoring force exceed the transverse repulsive force exerted on a grain by its downstream neighbors, i.e.,

$$\sum_{k<j} C_{jk} + C_{j,j+1} < 0 \qquad (20a)$$

where

$$C_{jk} \equiv -\frac{1}{2}\frac{\partial^2 \Phi(r_\perp = 0, z_{jk})}{\partial r_\perp^2} \qquad (20b)$$

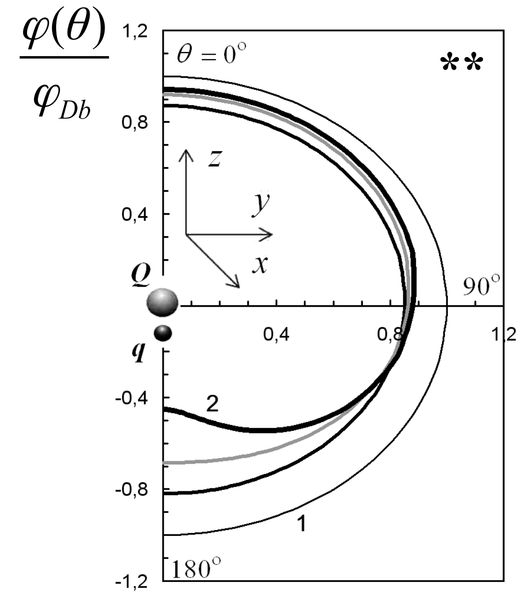
FIG. 6. Transverse restoring forces from the ion clouds acting on the lower particulates as a function of the displacement in the x direction for different ion mean free paths. (1) $\lambda_{\mathrm{mfp}} = 50$ μm, $Z_i = 0.58 Z n_i/\rho$, $d_i = 0.49a$; (2) $\lambda_{\mathrm{mfp}} = 100$ μm, $Z_i = 0.43 Z n_i/\rho$, $d_i = 0.40a$; (3) $\lambda_{\mathrm{mfp}} = 200$ μm, $Z_i = 0.44 Z n_i/\rho$, $d_i = 0.38a$. Symbols denote the MC results, solid lines indicate the forces for positive point charges with parameters Z_i, d_i replacing the ion cloud. (4) The dashed line is the repulsion force between two layers for $n_t = \varrho$.

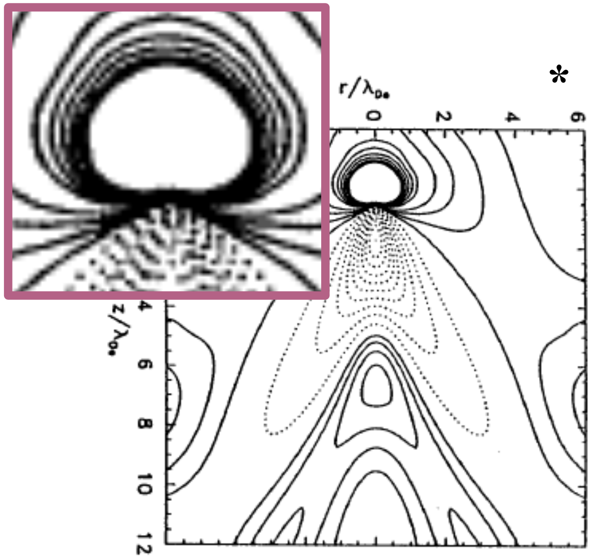
- ✓ only radial component
  of dust kinetic energy was observed

ANISOTROPIC QUASI-DIPOL-DIPOL INTERACTION

Numerical, analytical and experimental studies of spatial distribution of electrostatic potential around a dust particle in an anisotropic plasma flow:

[V. A. Schweigert, *et all*, Phys. Rev. E (1996)]
[V. A. Schweigert, *et all*, Phys. Rev. Lett., (1998)]
[S. A. Maiorov, S. V. Vladimirov, Phys. Rev. E (2000)]
[S. V. Vladimirov, S. A. Maiorov, Phys. Rev. E (2003)]
[W.J. Miloch, *et all*, Phys. Rev. E (2008)]
[I.H. Hutchinson, Phys. Rev. E (2012)]
[С.А. Майоров, Б.А. Клумов, Кр. сооб. ФИАН, (2013)]
[V.V. Zhakhovskii, V.I. Molotkov, *et all*, JETP Lett., (1997)]
[Y. Hayashi, K. Tachibana, J.Vac.Scl.Technol.A (1996)]
[C. Killer, *et all*, Phys. Rev. B (2011)]
[A. Aschinger, J. Winter, NJP (2012)]
[T.W. Hyde, *et all*, Phys. Rev. E (2013)]
[A.V. Ivlev, , *et all*, PRX (2015)]

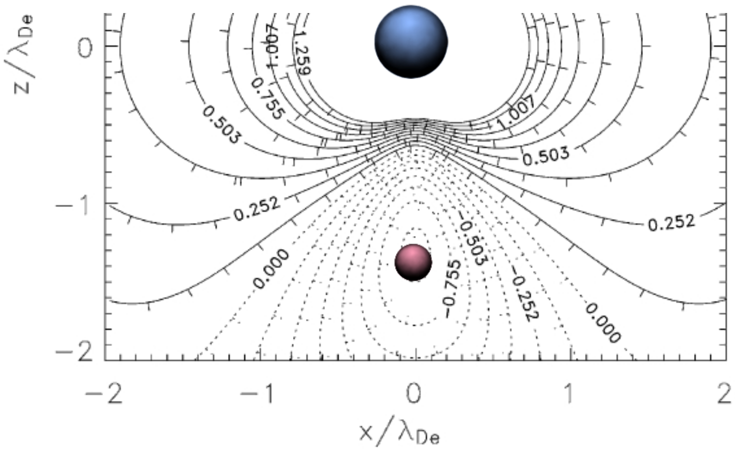




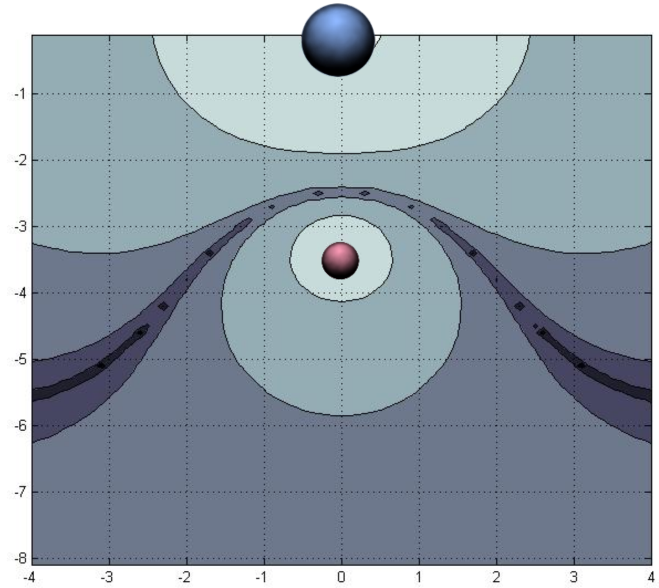
* [M. Lampe, *et all*, Physics of plasmas (2000)]

** [Lisina I.I., Vaulina O.S. // EPL, **103** (2013) 55002]

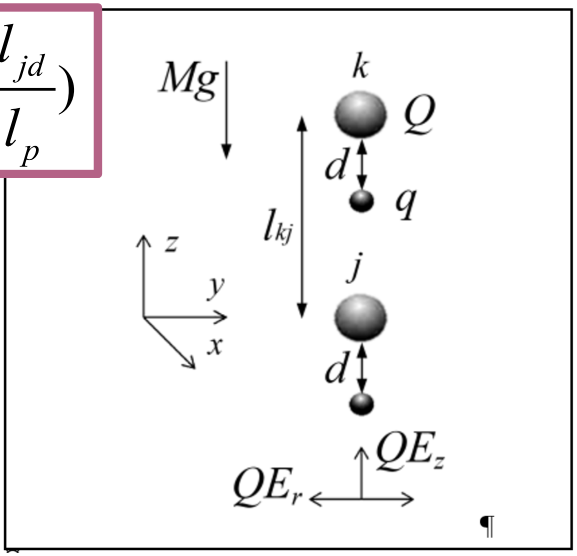
ANISOTROPIC QUASI-DIPOL-DIPOL INTERACTION



[M. Lampe, G. Joyce, G. Ganguli, IEEE Trans. Plasma Sci.(2005)]



$$\varphi_{kj}(l_{kj},\ l_{jd}) = \frac{Q}{l_{kj}}\exp(-\kappa\frac{l_{kj}}{l_p}) + \frac{q}{l_{jd}}\exp(-\kappa\frac{l_{jd}}{l_p})$$



$$\boldsymbol{q}^* = q_W / Q_p,$$

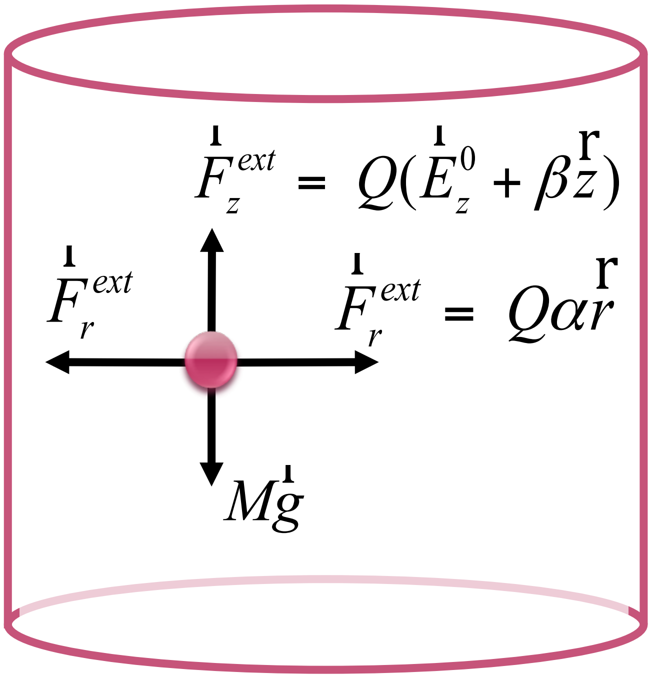
$$F_{kj} = Q\varphi_{kj}^{(1)}(l_{kj}, l_{jd}).$$

$$\boldsymbol{d}^* = d_W / l_p$$

$$F_{jk} \neq F_{kj}$$

INTERACTING PARTICLES IN AN ELECTROSTATIC TRAP

We put N particles with quasi dipol-dipol interaction into a linear trap



$$F_{int}(l) = -Q\frac{\partial\varphi}{\partial l}$$

Equations of motion

$$M_{dp}\ddot{\mathbf{r}} = \mathbf{R}$$

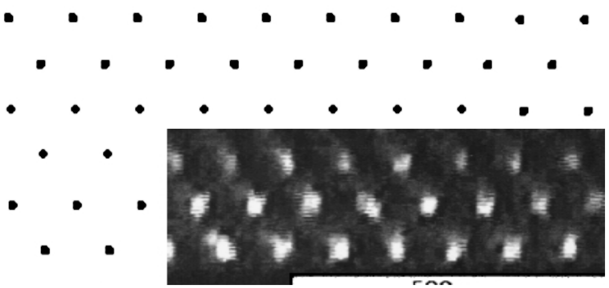
The statistical approach proposed by Langevin, allows us write the stochastic equations of motion for each particle

$$M\frac{d^2\vec{l}_k}{dt^2} = \sum_j F_{int}(l)\Big|_{l=|\vec{l}_k-\vec{l}_j|}\frac{\vec{l}_k-\vec{l}_j}{|\vec{l}_k-\vec{l}_j|} - M\nu_{fr}\frac{d\vec{l}_k}{dt} + \vec{F}_{ext} + M\vec{g} + \vec{F}_{br}$$

NONRECIPROCAL QUASI-DIPOL-DIPOL INTERACTION

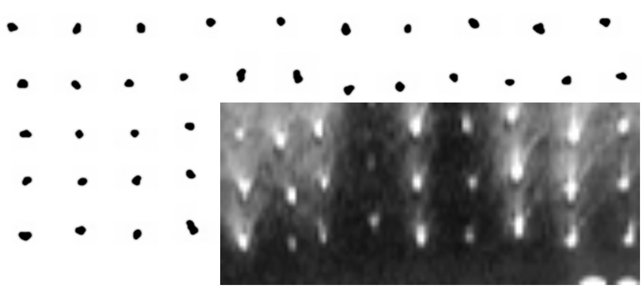
Fragments of vertical cross section of five-layer structures (particle tracks in XZ-plain, $\Delta Y \sim 0.3\, l_p$) :

$q = -\,0.16\,Q,\; d/l_p = 0.25$



[Hayashi Y., 1999]

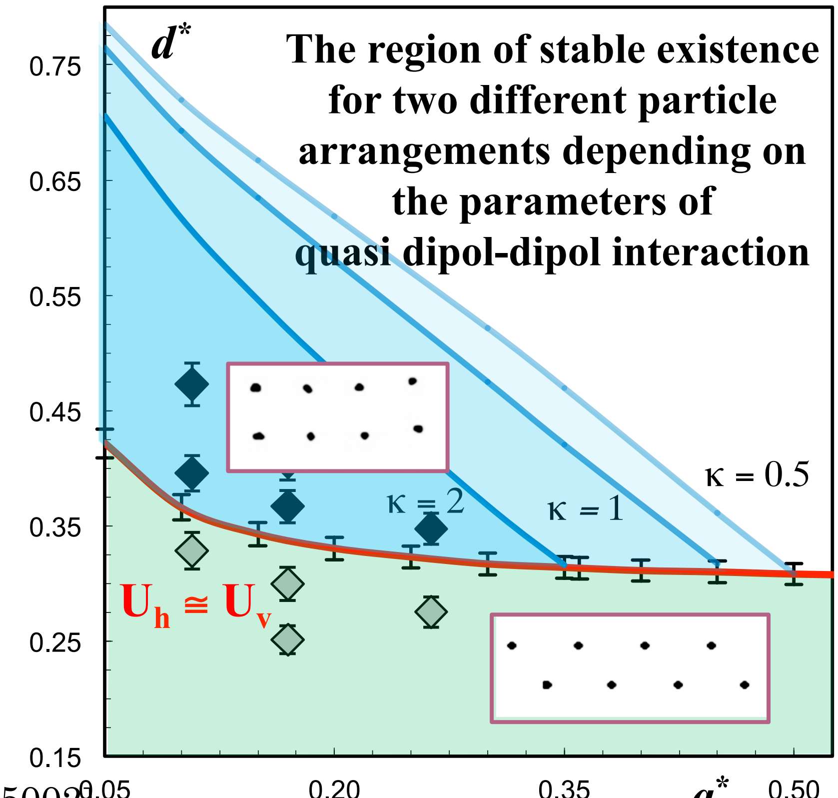
$q = -\,0.16\,Q,\; d/l_p = 0.37$



[Hayashi et al., 1999]

The criterion for the particle arrangements:

$$\mathbf{U}_\Sigma \equiv \mathbf{U}_\mathbf{v} < \mathbf{U}_\mathbf{h}\;, \qquad \mathrm{U}_\Sigma = \sum_{k,j;k\neq j} U_{kj}$$



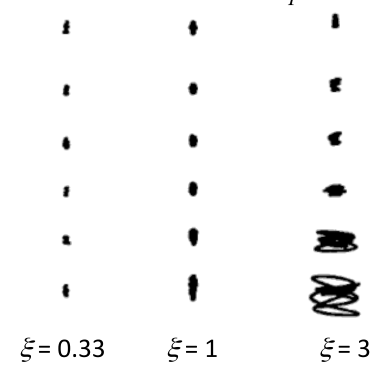
[Lisina I.I., Vaulina O.S. // EPL, **103** (2013) 55002]

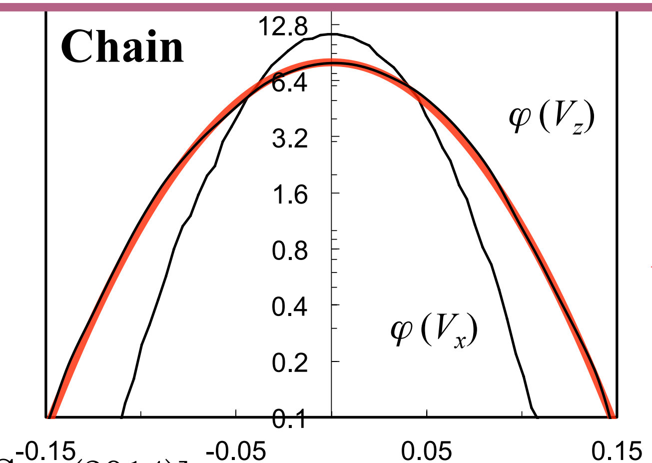
NONRECIPROCAL QUASI-DIPOL-DIPOL INTERACTION

- particle tracks

Kinetic temperature $\delta K = (K - \frac{3}{2}T) \geq 0$

$q = -\ 0.15\ Q,\ \ d/l_p = 0.2$





$\frac{T}{2} = 0.05\ \text{eV}$

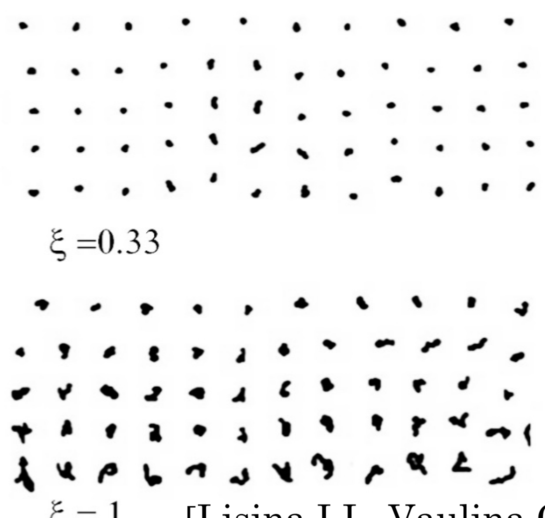
K_x =0.05eV

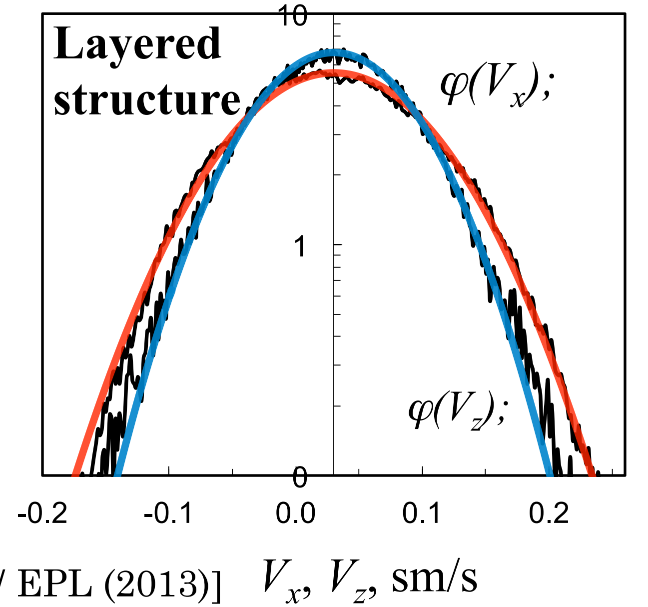
K_z=0.1 eV

$K_z \geq K_x \sim K_y$

[Lisina I.I., Vaulina O.S. // Phys. Scr. (2014)]

$q = -\ 0.16\ Q,\ \ d/l_p = 0.37$





$\frac{T}{2} = 0.014\ \text{eV}$

K_x =0.14 eV

K_z =0.21 eV

$K_z > K_x \sim K_y$

[Lisina I.I., Vaulina O.S. // EPL (2013)]

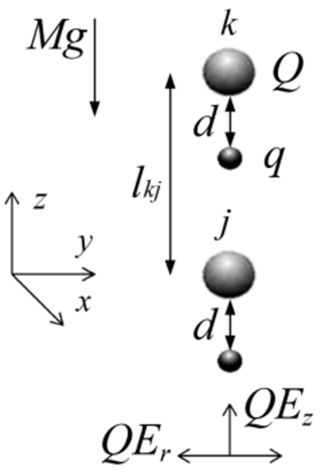
TWO PARTICLES

$$M\frac{d^2\xi_1^{z(x)}}{dt^2} = -M\nu_{fr}\frac{d\,\xi_1^{z(x)}}{dt} - Q\beta^{z(x)}\,\xi_1^{z(x)} - a_1^{z(x)}(\xi_1^{z(x)} - \xi_2^{z(x)}) + F_{b1}^{z(x)}$$

$$M\frac{d^2\xi_2^{z(x)}}{dt^2} = -M\nu_{fr}\frac{d\,\xi_2^{z(x)}}{dt} - Q\beta^{z(x)}\,\xi_2^{z(x)} - a_2^{z(x)}(\xi_2^{z(x)} - \xi_1^{z(x)}) + F_{b2}^{z(x)}$$

$a_1^{z} = F_{12}^{(1)},\ a_2^{z} = F_{21}^{(1)}$

$a_1^{x(y)} \approx F_{12}/l_p\ ,\ a_2^{x(y)} \approx F_{21}/\,l_p$



the correlation equations for Brownian force :

$<F_{b1}> = <F_{b2}> \equiv 0,\ <F_{b1}\,F_{b2}> = 0,$

$<F_{b1}\,V_2> = <F_{b2}\,V_1> \equiv 0,\ <F_{b1}\,\xi_2> = <F_{b2}\,\xi_1> \equiv 0,$

$<F_{b1}\,\xi_1> = <F_{b2}\,\xi_2> \equiv 0,\ <F_{b1}\,V_2> = <F_{b2}\,V_1> \equiv 0;$

$F_{kj}^{(1)}$ - The first derivative of the F_{kj} at a distance l_p,

$V_{1(2)} = \frac{d\,\xi_{1(2)}}{dt}$ - velocities of the *1st* and the *2nd* particles respectively.

$< >$ denotes time averaging for $t \rightarrow \infty$.

TWO PARTICLES

Bearing that $MV_{1(2)}{}^2 \equiv T_{1(2)} = T + \delta T_{1(2)}$, $\nu_{fr}\delta T_{1(2)} = \nu_{fr}T_{1(2)} - \langle V_{1(2)}F_{b1(2)}\rangle$, and as the particles move along closed trajectories then $\langle \xi_1 V_1 \rangle = \langle \xi_2 V_2 \rangle \equiv 0$, which lets us go to equations describing the additional energy "swap"

$$\delta T^{z(x)} \equiv \frac{\delta T_1{}^{z(x)} + \delta T_2{}^{z(x)}}{2} = \frac{0.5\,T(a_1^{z(x)} - a_2^{z(x)})^2}{0.5(a_1^{z(x)} + a_2^{z(x)})^2 + (a_1^{z(x)} + a_2^{z(x)} + 2\beta^{z(x)})M\nu_{fr}^2}$$

and the energy redistribution between the particles

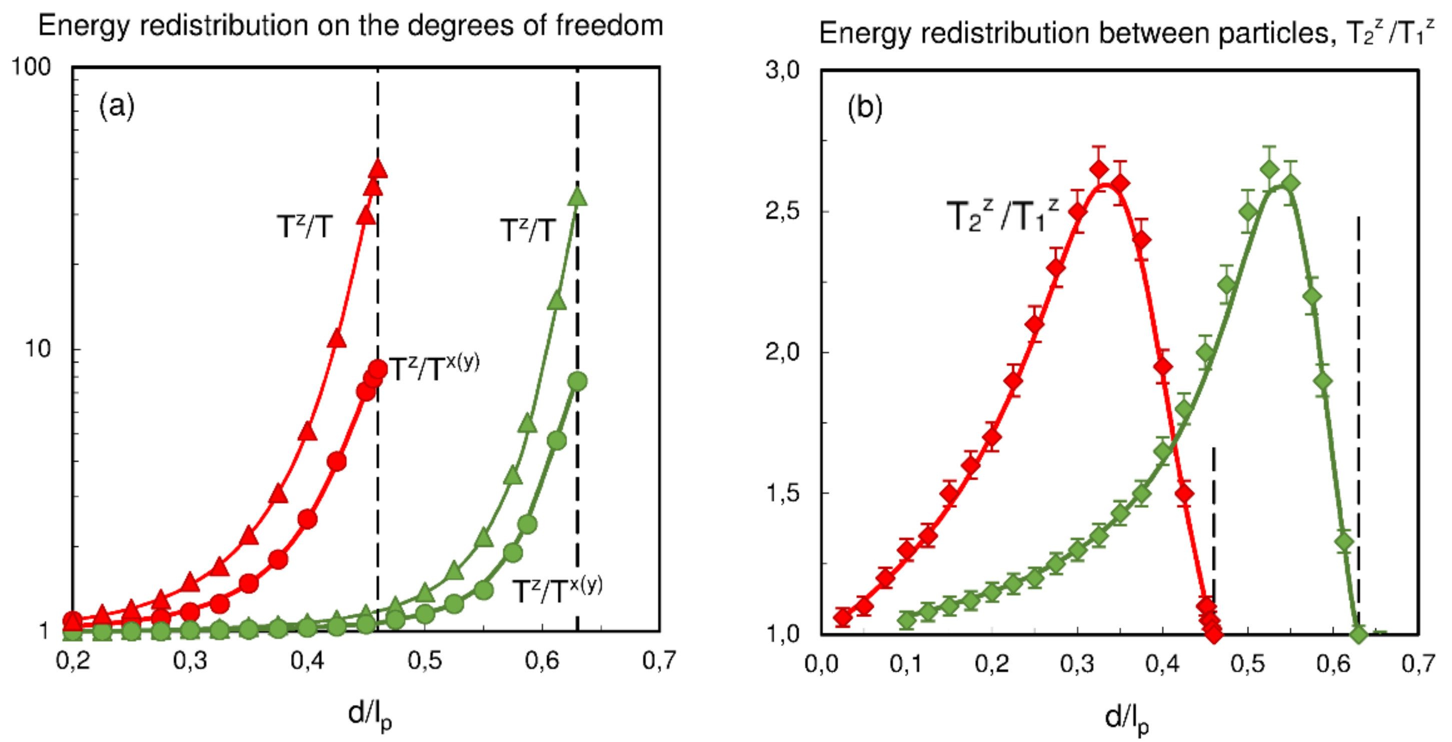
$$\frac{T_2}{T_1} \equiv \frac{T + \delta T_2}{T + \delta T_1} = \frac{1 + \delta T/T + \Delta T/T}{1 + \delta T/T - \Delta T/T}$$

As well as the energy redistribution on the degrees of freedom

$$\frac{T^z}{T^x} \equiv \frac{T + \delta T^z}{T + \delta T^x}$$

When $(a_1^{z(x)} + a_2^{z(x)}) \to 0$ the ratio $\Delta T^{z(x)}/T \to \infty$. In this case, the redistribution of energy between two particles becomes impossible and the system completely destroyed.

THEORY VS SIMULATION



$|q^*| = 0.3$ (red)

$|q^*| = 0.1$ (green)

$\beta^{x(y)}/\beta^{z} = 3.5$

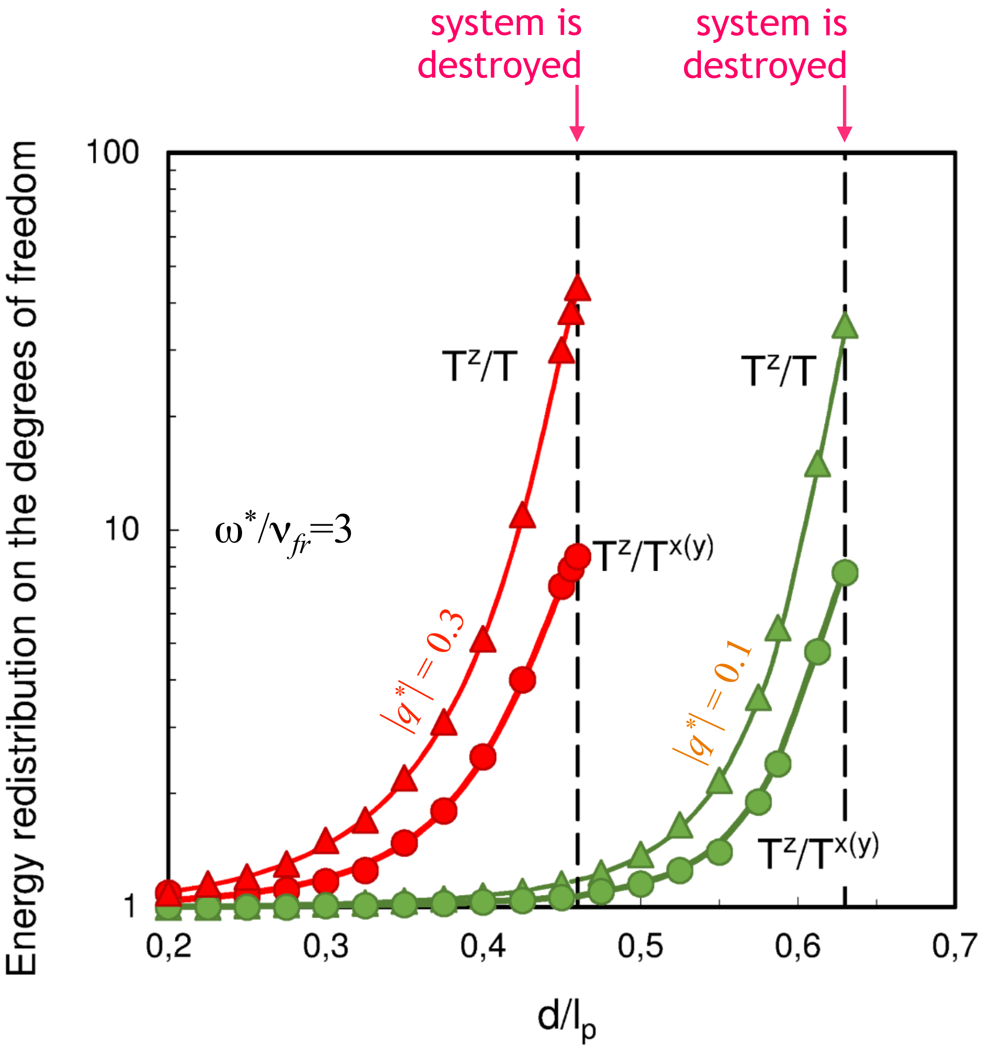
$\chi \cong 3$

The analytical solutions are illustrated by solid curves.

The simulation results are represented by symbols.

The dashed lines indicate the value of d^* when the system is destroyed due to development of vertical instability.

THEORY VS SIMULATION

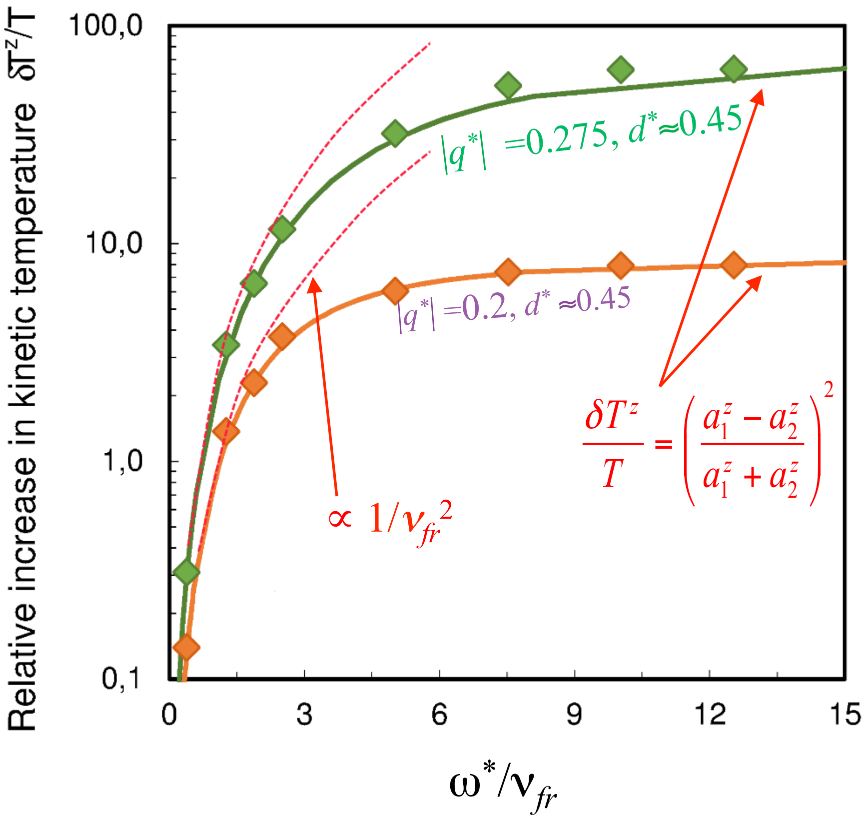


The proposed linear theory is in good agreement with the simulation results, even at high heating (when the kinetic energy *K* of particles much higher than the thermostat temperature *T*)

The system is completely destroyed when

$$(\partial F_{12}/\partial z + \partial F_{21}/\partial z) \to 0$$

THEORY VS SIMULATION



The swap in particle energy is due to the non conservativeness of the dust particle system.

Due to results obtained are the strong heating is possible when there are

- attraction forces between dust grains and
- friction forces.

If nonreciprocal forces are the repulsive forces, the kinetic temperatureof particle system can not be increased more than twice:

$$\partial T \approx T$$

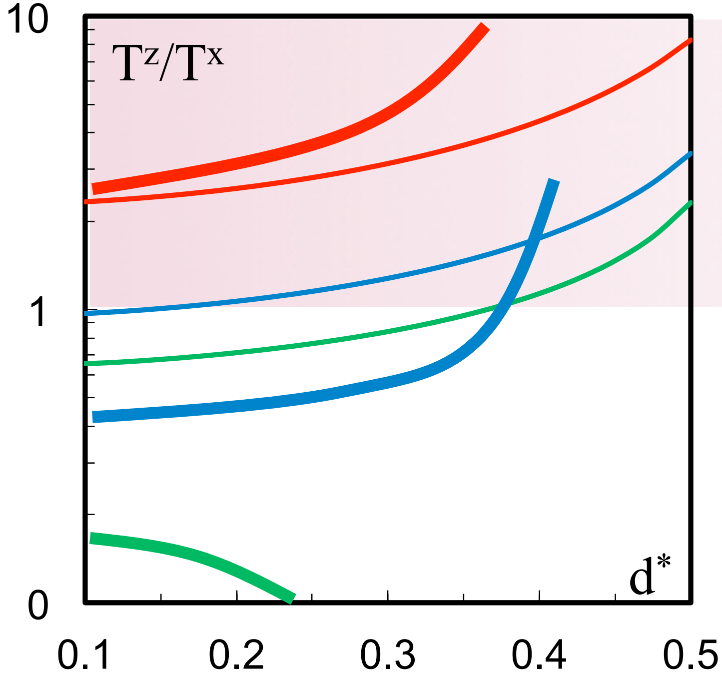
When $\nu_{fr} \to 0$
the growth of the kinetic energy is restricted due to their electrostatic interactions and random forces :

$$\delta T^{z(x)} \equiv T\,(a_1^{z(x)} - a_2^{z(x)})^2 / (a_1^{z(x)} + a_2^{z(x)})^2 = \text{constant}$$

When $\nu_{fr} \to \infty$, then $\nu_{fr}^{-1} \to \infty$

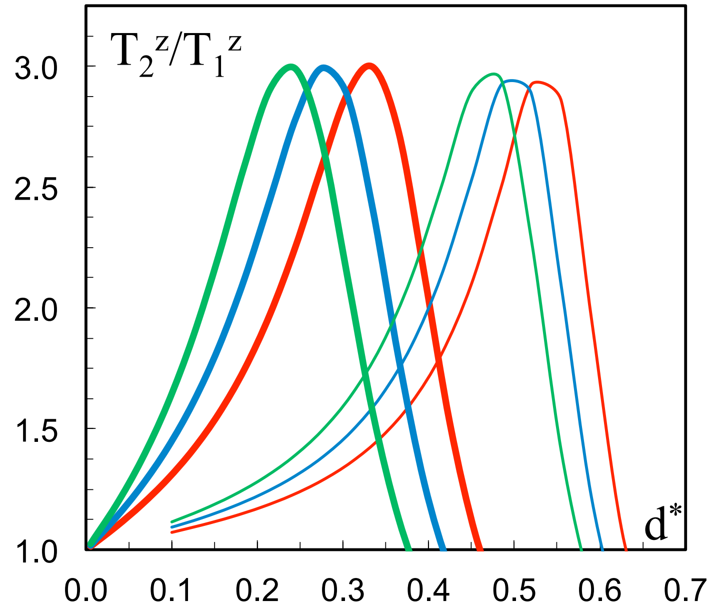
$$\partial T^{z(x)} \propto \nu_{fr}^{-2} \to 0, \quad T_2 / T_1 \to 1$$

THEORY VS EXPERIMENTS



O.S. Vaulina *et al.*, *Phys. Scr*. 2011
A. Aschinger, J. Winter, *NJP* 2012
A.A. Samarian *et al.*, *PRE* 2001

J.B. Pieper, J. Goree, *PRL* 1996
A.K. Mukhopadhyay, J. Goree, *PRE* 2014



$\kappa_1=\kappa_2\equiv0$

$\kappa_1=1.5, \kappa_2=0$

$\kappa_1=2, \kappa_2=0$

thin line: $q^*= 0.1$

bold line: $q^*= 0.3$

THANKS FOR THE ATTENTION!

QUESTIONS ARE WELCOME!

ELECTROSTATIC POTENTIAL AROUND A SPHERICAL BODY IN PLASMA

$U = eZ\varphi(l)$ is the potential energy of interaction between particles (pair approximation)

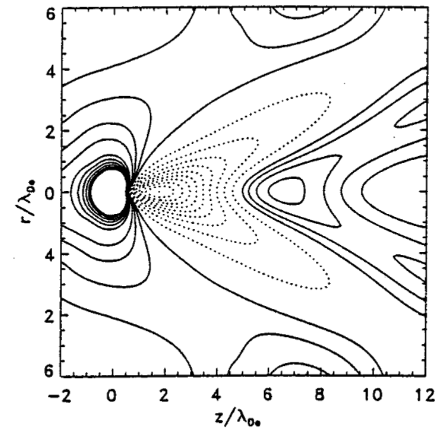
- A simple Yukawa model (particle size $a<<\lambda$)

$$\varphi_Y(l) = \frac{Ze}{l}\exp\left(-\frac{l}{\lambda}\right)$$

- Macroparticle in a bulk plasma:

$$\varphi(l) = \varphi_Y(l) + \varphi_{ad}(l)$$

- ❑ $\varphi(l) \propto l^{-2}$ in a collisionless plasma [*Allen (1992), Khrapak et al. (2001)*]
- ❑ $\varphi(l) \propto l^{-1}$ in a collisional (weakly) regime [*Filippov et al. (2007), Khrapak et al. (2008)*]
- ❑ $\varphi(l) = Ze\left[A\ \exp(-\kappa_1 l) + A_2 \exp(-\kappa_2 l)\right]/l$ with ionization sources [*Filippov et al. (2007)*]



Lampe et al., Phys.Plas.(2000)

- Test particle in a plasma flow:

- ❑ an attractive part due to ion focusing
- ❑ $\varphi(l) \propto l^{-3}$ in a collisionless plasma [*Montgomery et al., PoP(1968), Kompaneets et al., PoP(2009)*]
- ❑ $\varphi(l) \propto l^{-2}$ in a collisional regime [*Stenflo et al., Phys. Fluids (1973), Chaudhuri et al., PoP(2007)*]