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Effects of Disorder on Electron Heating in Ultracold Plasmas

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Yu.V. Dumin[1,2] & A.T. Lukashenko[3]

[1] *Lomonosov Moscow State University, Moscow, Russia*
[2] *Space Research Institute of Russian Academy of Sciences, Moscow, Russia*
[3] *Nimbl Academy, Astana, Kazakhstan*

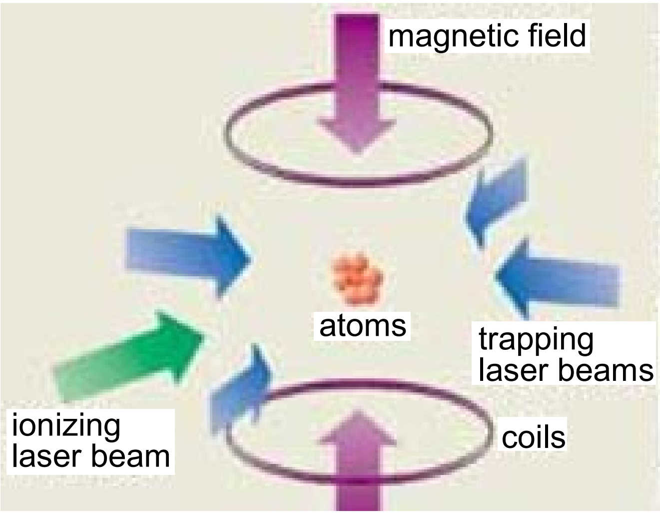
Introduction - 1

- Creation of plasmas with large values of the Coulomb's coupling parameter

$$\Gamma = \frac{e^2 N^{1/3}}{k_{\mathrm{B}} T}$$

is a long-standing problem of plasma physics.

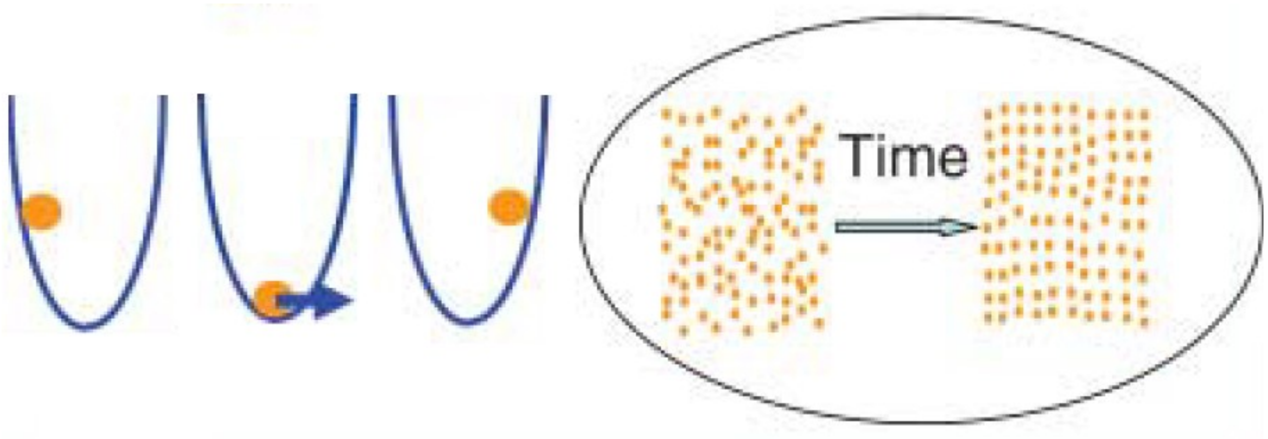
- A radically new approach to this problem, suggested in the early 2000's, is the ionization of ultracold gases ($10^{-4} - 10^{-5}$ K) produced in the magneto-optical traps.
  – Since the ionizing laser irradiation can be tuned very close to the ionization threshold, it was initially expected that the electron coupling parameter can easily achieve the values as large as a few tens or hundreds.



  – Unfortunately, it was found already in the first experiments that the electron temperature (or kinetic energy) experienced a violent spontaneous increase by a few orders of magnitude. As a result, the electron coupling parameter Γ_e did not exceed the values about $0.2 - 0.4$.

Introduction - 2

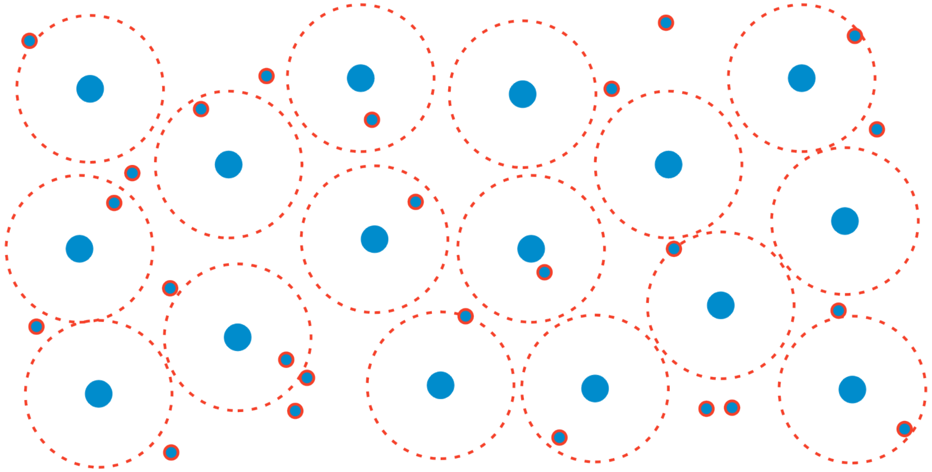
- A commonly-accepted explanation of this effect is based on the so-called mechanism of "disorder-induced heating" (DIH) [D. Gericke, M. Murillo, *Contrib. Plas. Phys.*, v.**43**, p.298 (2003)]:



  – Charged particles tend to move to the positions with minimal potential energy, *i.e.*, to form a quasi-regular structure.
  – Since a total energy of the system is conserved, reduction of the potential energy results in the increase of kinetic energy (and temperature) of the particles.

Introduction - 3

- To get around the disorder-induced heating, it was suggested the ultracold plasmas to be produced initially in a quasi-regular state. This can be done by the following two-step process:



  – Firstly, the ultracold atoms are excited to the Rydberg states and experience the so-called Rydberg blockade (when an already-excited atom shifts the energy levels of nearby atoms and, thereby, makes impossible their excitation to the same state). As a result, a system of the well-separated Rydberg atoms is formed.

  – Secondly, these Rydberg atoms are ionized by an additional laser beam and, thereby, form a quasi-regular (crystalline-like) lattice of ions. So, one can expect that there should be no a subsequent disorder-induced heating in such system.

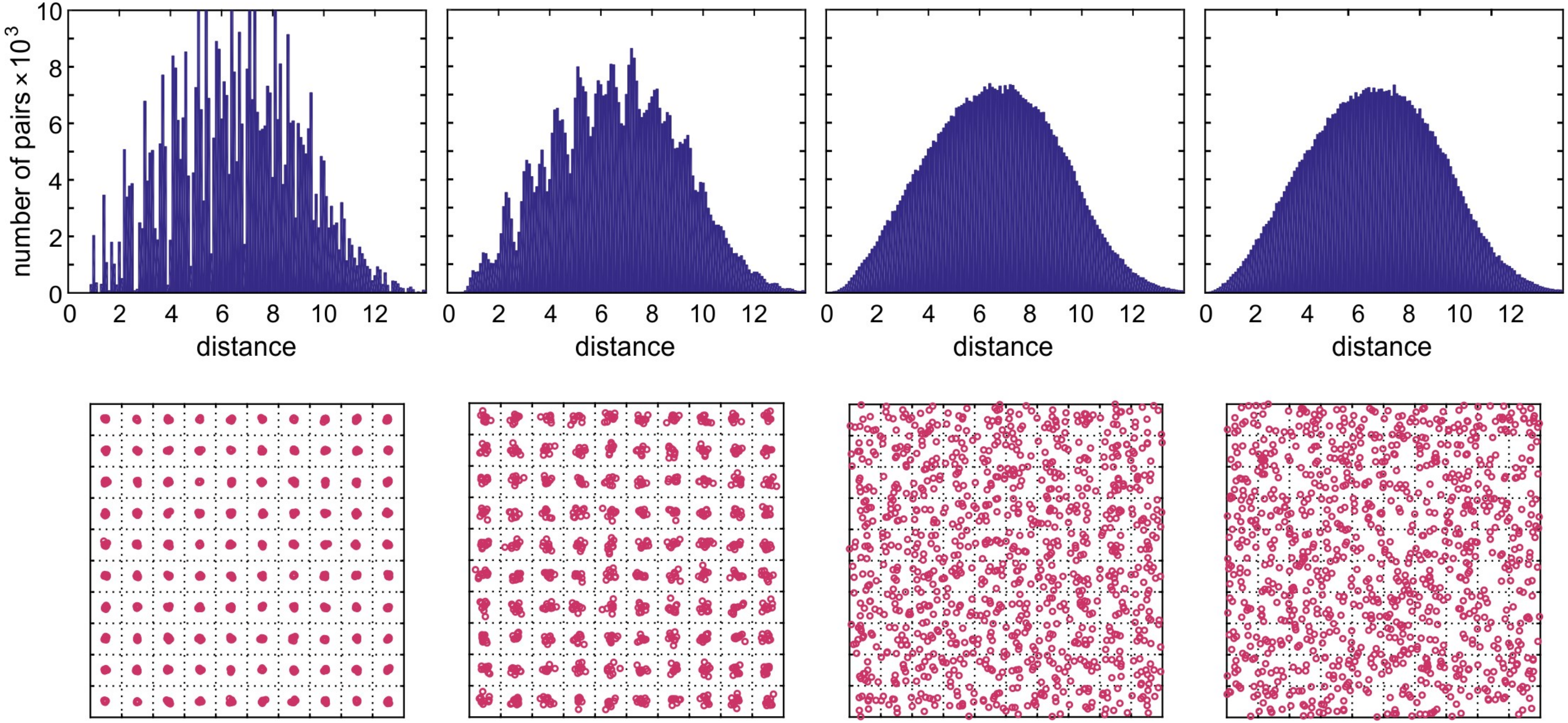
Introduction - 4

- Experimental implementation of the two-step plasma formation with Rydberg blockade was undertaken, *e.g.*, in work [M. Robert-de-Saint-Vincent, *et al. Phys. Rev. Lett.*, **v**.110, p.045004 (2013)].
  - Unfortunately, no noticeable reduction of the electron temperature was detected.
  - It remained unclear if this was caused by
    (i) the insufficient diagnostic facilities to measure the electron temperature or
    (ii) a failure of the entire theoretical concept.

- So, it was the aim of our work to simulate numerically a relaxation of the electron velocities against the ionic background with various types of arrangement.
  - Thereby, we aimed to quantify the efficiency of mitigation of the disorder-induced heating by the two-step plasma formation protocol and, therefore, to estimate a perspective for the creation of strongly-coupled ultracold plasmas.

Simulation Setup

- The electron dynamics was simulated against the ionic background with different degrees of regularity:



$\sigma_{\rm reg} = 0.03$ $\sigma_{\rm reg} = 0.1$ $\sigma_{\rm reg} = 0.3$ $\sigma_{\rm reg} = 1$

$$m_e \frac{d^2\mathbf{r}_i}{dt^2} = -\sum_j e^2 \frac{\mathbf{r}_i - \mathbf{R}_j}{|\mathbf{r}_i - \mathbf{R}_j|^3} + \sum_{k \neq i} e^2 \frac{\mathbf{r}_i - \mathbf{r}_k}{|\mathbf{r}_i - \mathbf{r}_k|^3}$$

Dimensionless variables used in the simulations:

- the unit of length is a distance between ions in the unperturbed lattice: l

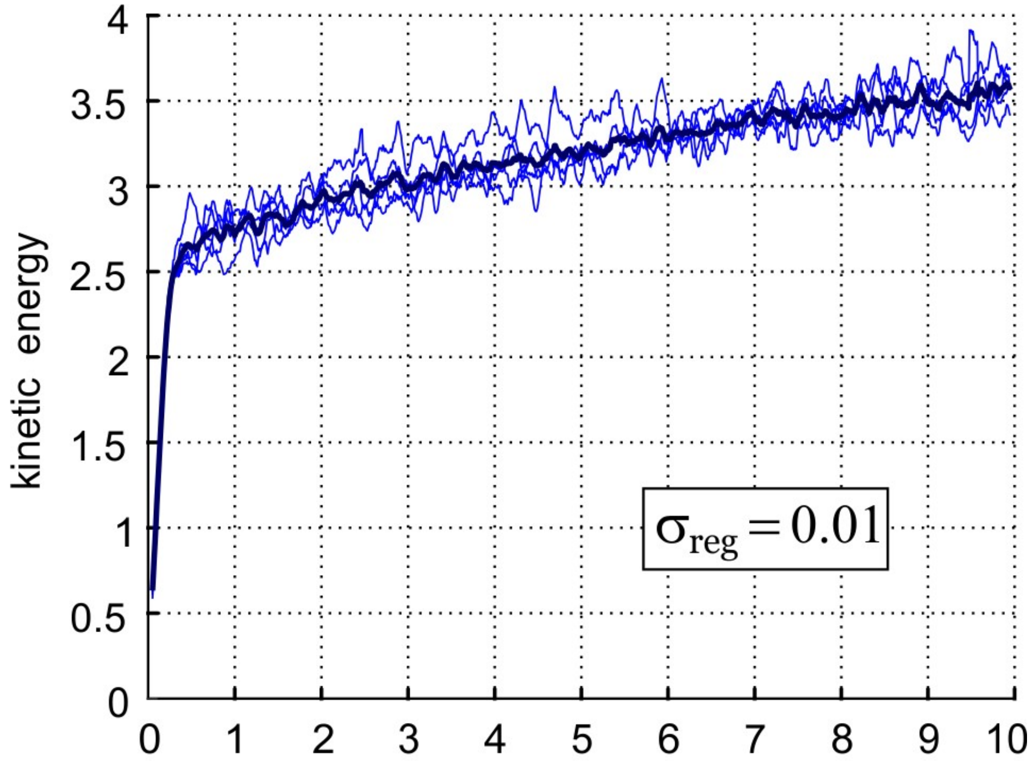
- the unit of time is proportional to the Keplerian frequency of revolution of an electron about the nearest ion or, up to numerical factor on the order of unity, the inverse plasma frequency:

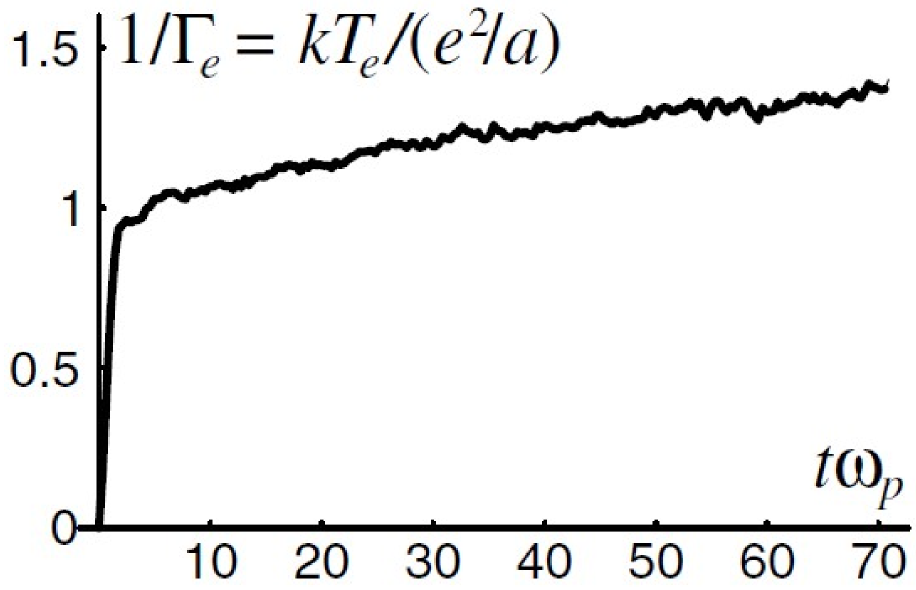
$$\tau = \sqrt{\frac{m\,l^3}{e^2}} = \frac{\sqrt{4\pi}}{\omega_{pl}}$$

- the unit of energy is the characteristic Coulomb's interparticle energy: $\tilde{E}_p = e^2/l$

Results of Simulations - 1

- As expected, a temporal evolution of the electron kinetic energy (or temperature) exhibits two characteristic stages:
  - Firstly, the temperature sharply jumps (due to the “disorder-induced heating” or some other mechanism);
  - Then, the temperature continues to increase much more slowly (presumably, due to a heat release in the course of recombination).

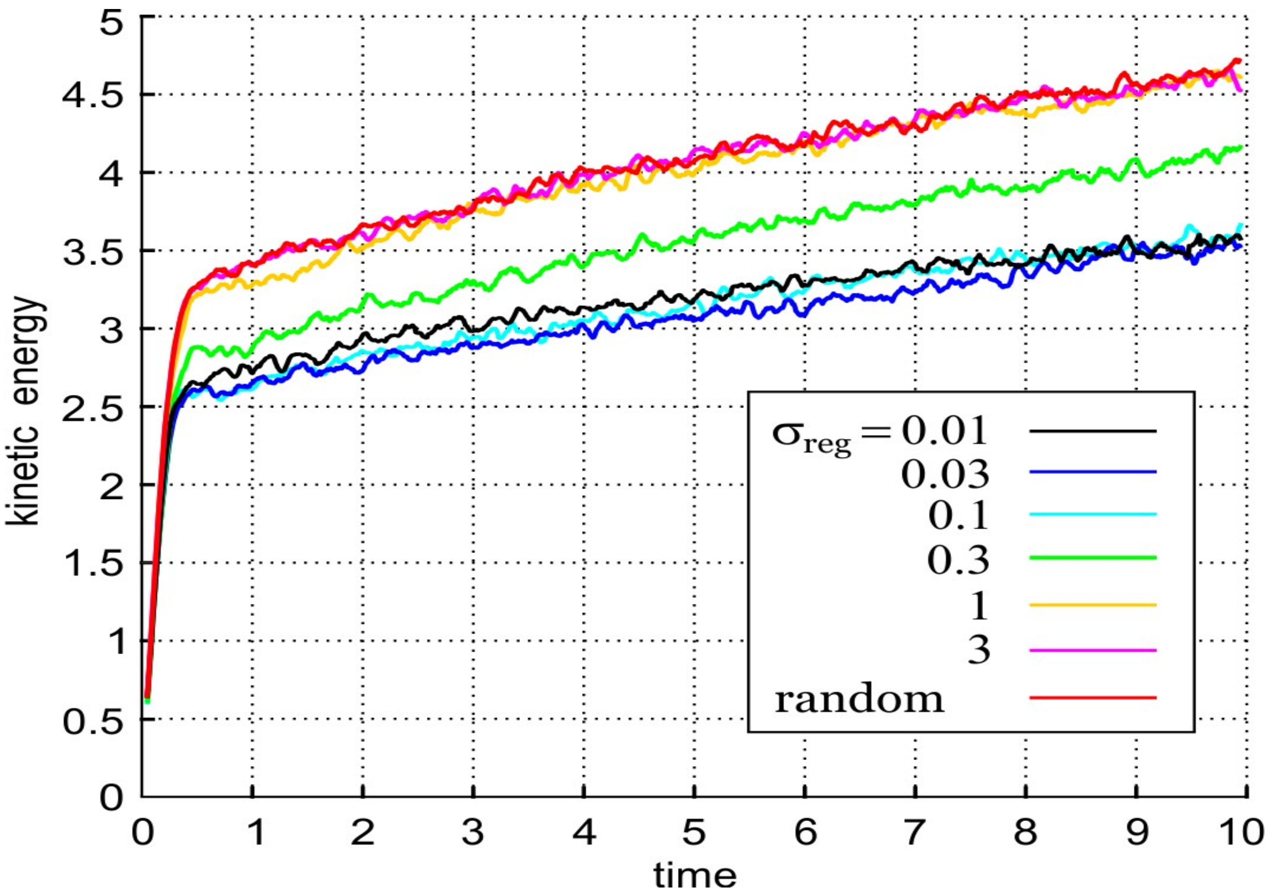




[Kuzmin & O'Neil, *Phys. Rev. Lett.*, v.**88**, p.065003 (2002)]

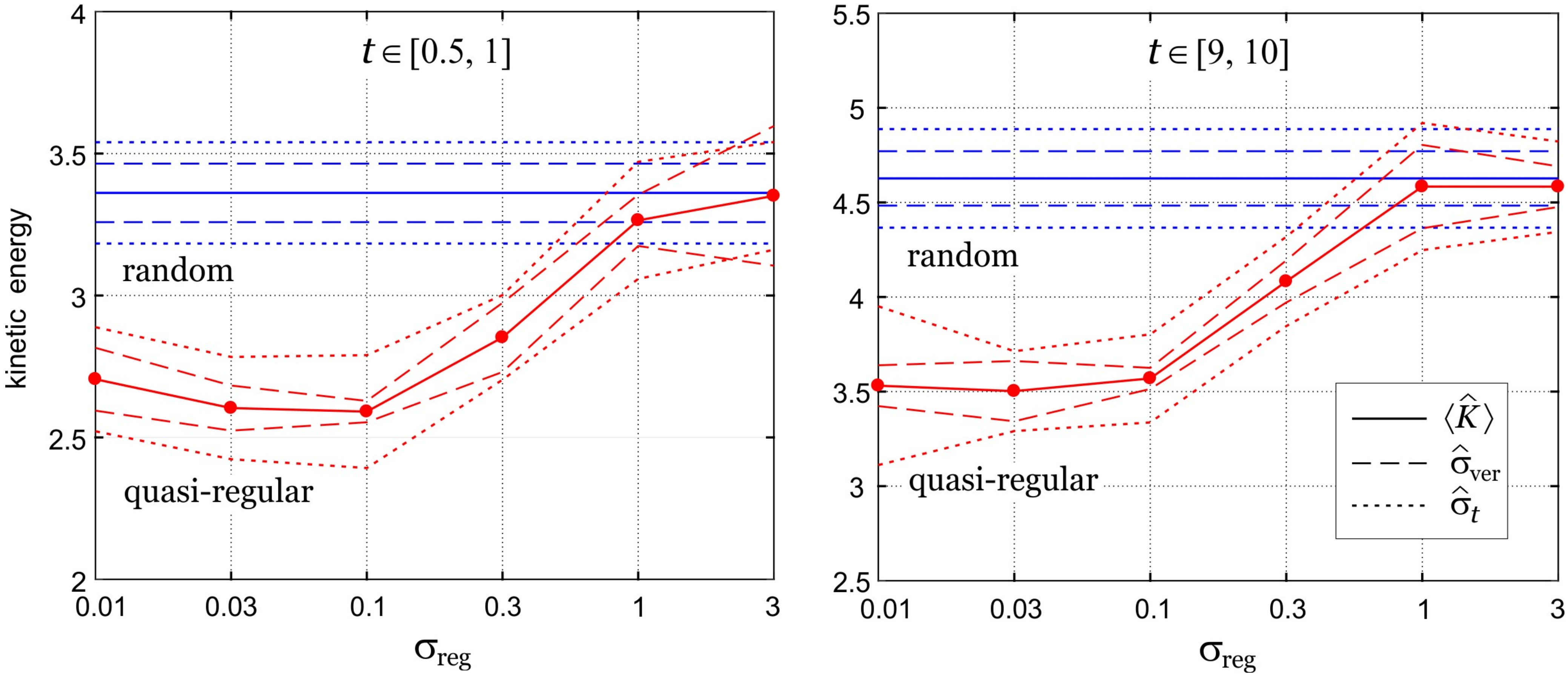
- In general, this is in agreement with earlier simulations for the case of random initial distribution of ions.

Results of Simulations - 2



- When the initial distribution of ions becomes more regular (*i.e.*, σ_{reg} decreases), both stages of the temperature increase are reduced.
  – But a magnitude of this reduction is relatively small.

Summary of Simulations



- To characterize the total effect, we introduced mean values of the electron kinetic energy established at the intervals $t \in [0.5, 1]$ (*i.e.*, immediately after the sharp jump) and $t \in [9, 10]$ (*i.e.*, after some period of recombination).
  – As is seen, both these quantities are reduced by ~30% when the distribution of ions transforms from a completely random to almost regular (crystalline-like).

Discussion and Conclusions:

1. Electron temperature exhibits a well-expressed transition from the case of random distribution of ions to the quasi-regular one.

- However, a magnitude of this effect is not so large as expected before; it was found to be only ~30%.
- Therefore, the method of two-step plasma formation with Rydberg blockade has a limited efficiency.

2. Of even greater interest is the fact that the initial jump of electron temperature remained considerable (by 1-2 orders of magnitude) when there was essentially no initial disorder.

- Therefore, the concept of “disorder-induced heating” looks doubtful.

3. An alternative explanation of the sharp initial jump can be based on the concept of “virialization”, which is insensitive to the degree of initial disorder.

- It is interesting to mention that the idea of “virialization” was suggested even before DIH [Yu.V. Dumin. *J. Low Temp. Phys.*, v.**119**, p.377 (2000)], but it did not attract a noticeable attention till now.