Stochastic electron dynamics in microdroplet plasma irradiated by an ultrashort, intense laser pulse

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Abstract

The use of sub-micro-sized mass limited targets in interaction with intense ultrashort femtosecond laser pulses is considered to be uniquely convenient approach for the development of a compact versatile pulsed source of secondary radiation. Innovative nanoand micro-sized targets, including droplets and micro clusters, allow effectively absorb laser energy, generate high energy electrons and, as a result, increase the production of accelerated ions, X-rays, neutrons, etc. In the case of the interaction of a laser pulse with nano/micro-sized targets, the determining mechanism of a large energy gain by electrons is the stochastic heating in the combined field of the laser pulse and the Coulomb field of the droplets. We focus on study of hot electron generation and particle acceleration to energies beyond the ponderomotive limit. The model describes the high energy particle generation as a result of multiple elastic electron scattering on an expanding charged cluster. The expected appearance of supra-ponderomotive electrons should lead to an increase in the hardness of X-ray radiation.

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Simulation setup

Pulse parameters:

$I = 2\times 10^{18} - 3.4\times 10^{19}\ W/cm^2$

$\lambda = 1\mu m$ $\quad\Rightarrow a_L = 0.85\sqrt{I\lambda_L^2/I_{18}\lambda_1^2} \approx 1.2-5$

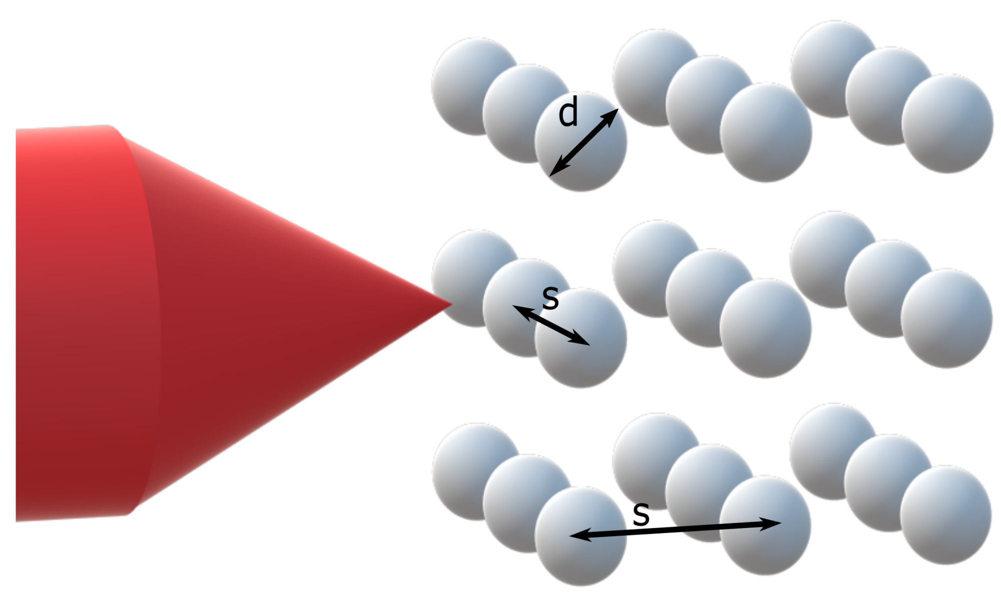
$\tau_{FWHM} = 10\ fs$

where $I_{18} = 10^{18}$ W/cm^2, $\lambda_1 = 1$ μm, I and λ_L is laser intensity and wavelength. The pulse propagates along the ***x*** axis and electric field ***E*** is linearly polarized along the ***y*** axis. In the transverse direction, the spatial profile of the pulse was a plane wave.

3D PIC simulation parameters:

Box:	$4.2\lambda_L \times 3.6\lambda_L \times 3.6\lambda_L$
Time step:	0.0047 fs
Spatial step:	$\lambda_L/600 \times \lambda_L/200 \times \lambda_L/200$
Partical in cell:	8
Duration of simulation:	60 fs

Clusters



The clusters were distributed randomly, but so that the average electron density was fixed for each simulation.
In the transverse direction, the boundary conditions for fields and particles were periodic. Due to the plane electromagnetic wave and periodic boundary conditions, we can say that we simulated a small region of interaction of a cluster gas with a laser with a large focal spot.

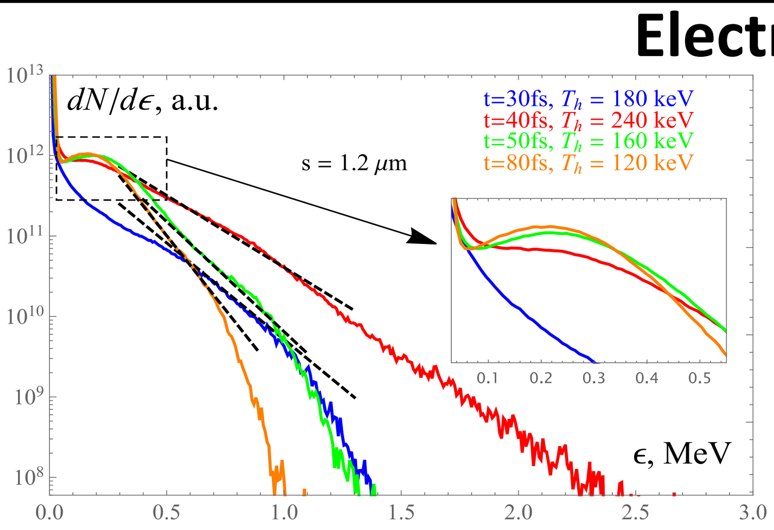
The short laser pulse pulls out electrons from skin-layer of the clusters and they became positively charged. The maximum of quasi-static Coulomb field decreases slowly after the laser leaves simulation box (for 50 fs, the field decreases by about 2 times). The electrons move stochastically in complex quasi-static field from different clusters.

Clusters electron density:	200n_{cr}
Diameter of clusters (d):	0.2 λ_L
Average distance between cluster centers (s):	1.2 λ_L
Average electron densiry:	0.48 n_{cr}

Type of ions: Au

Cluster ion density: $n_i=n_e/Z$, where Z=20

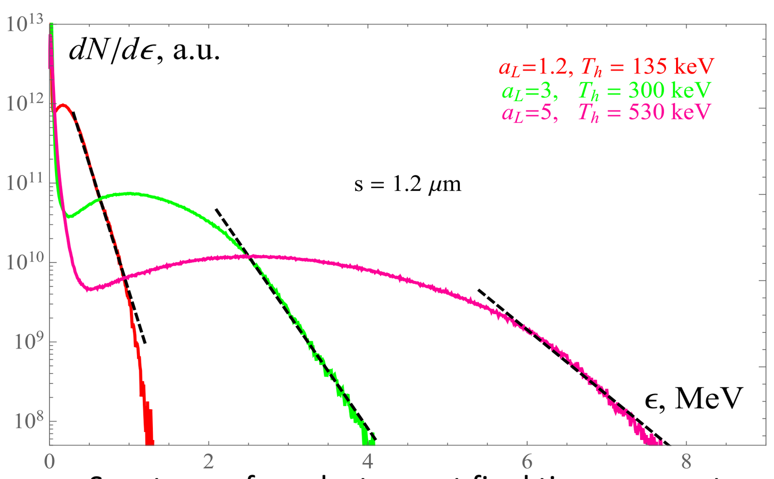
Electron Spectra



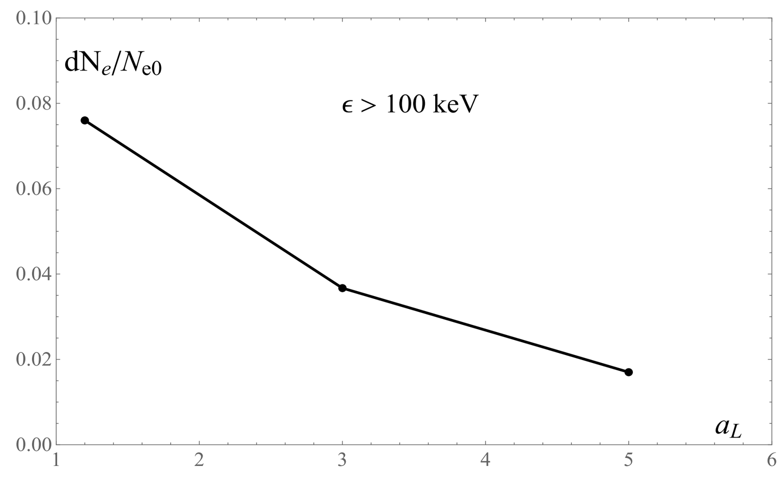
Spectrum of an electrons at different times for a_L = 1.2 and s/λ_L = 1.2

The electrons from plateau region contain significant part of electron energy, e.g. for a_L=1.2 it contains 21% of the total electrons energy and for a_L = 5 it contains 36% of the total electrons energy.

At a fixed laser pulse energy, it is more advantageous to have a larger focal spot with a lower intensity in order to obtain a larger number of electrons with energies above 100 keV.

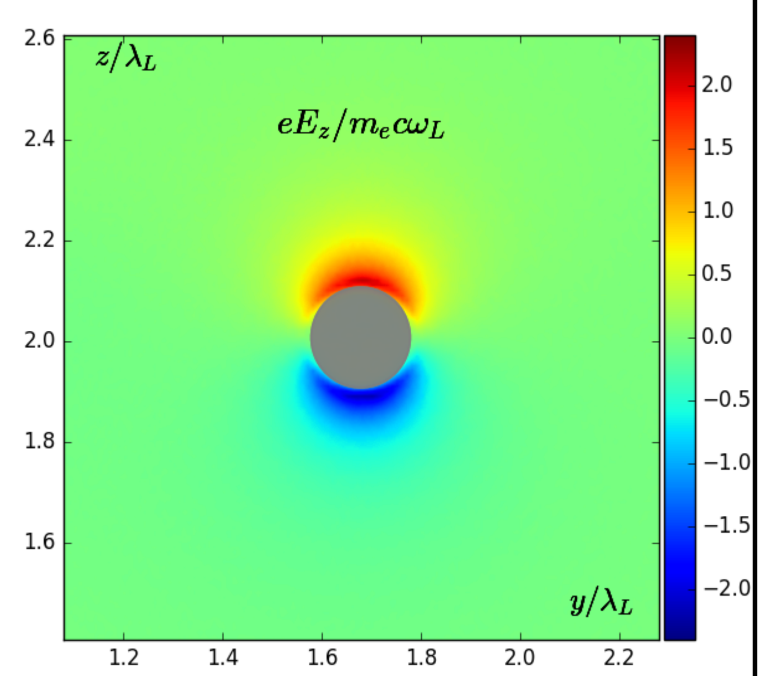


Spectrum of an electrons at final time moment (t=60 fs) at different laser intensity for s/λ_L = 1.2

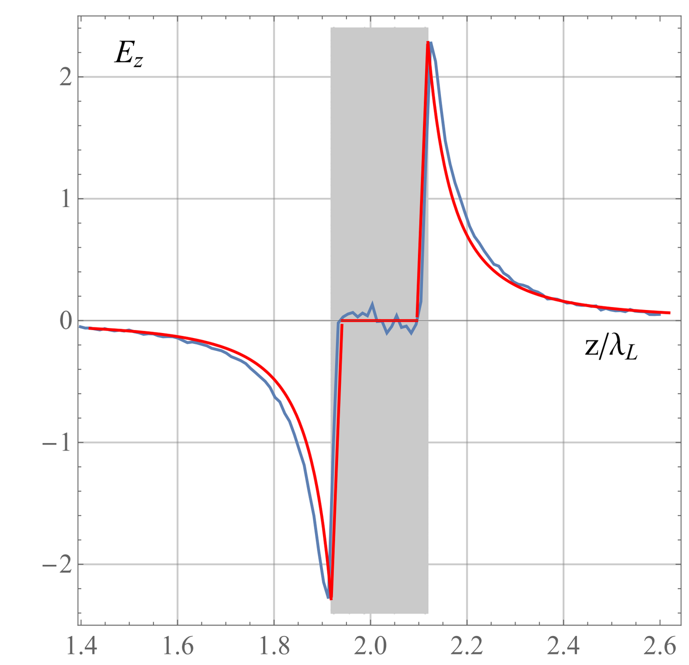


Fraction of electrons with energy more than 100 keV in relation to the total number of electron in focal spot for a_L = 1.2 and a fixed laser energy at final time moment (t = 60 fs).

Quasi-static Coulomb field

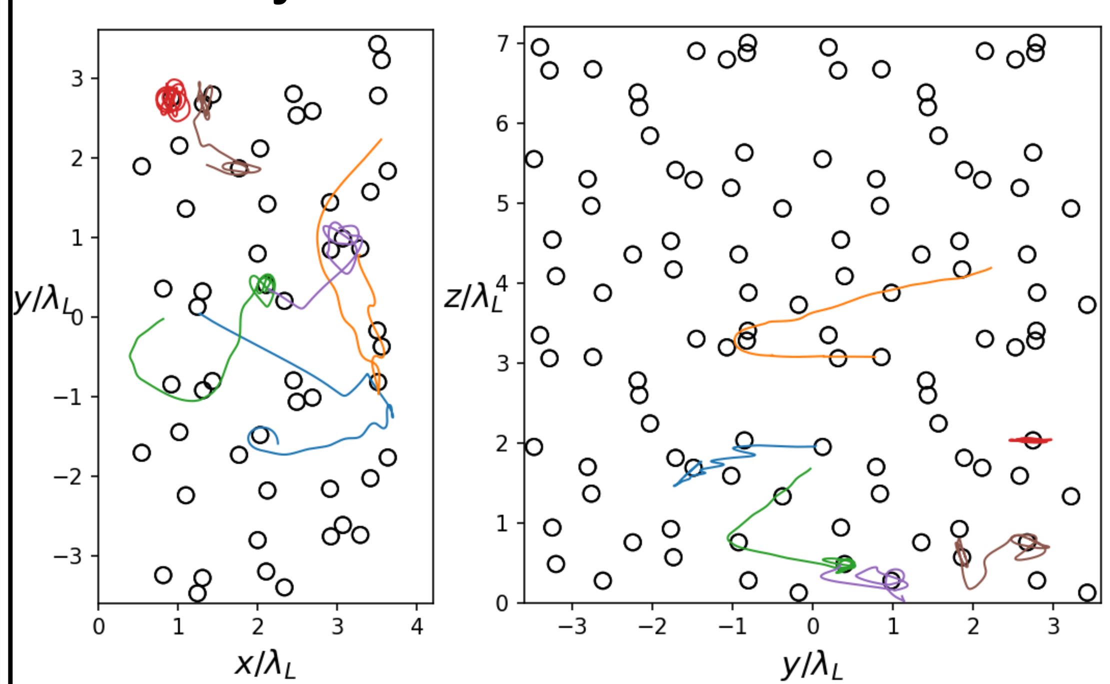


Time-averaged electric field E_z around one cluster in the transverse plane



Time-averaged electric field E_z around one cluster along the axis z (blue line) and approximation formula for the test particle method(red line)

Trajectories in PIC simulation

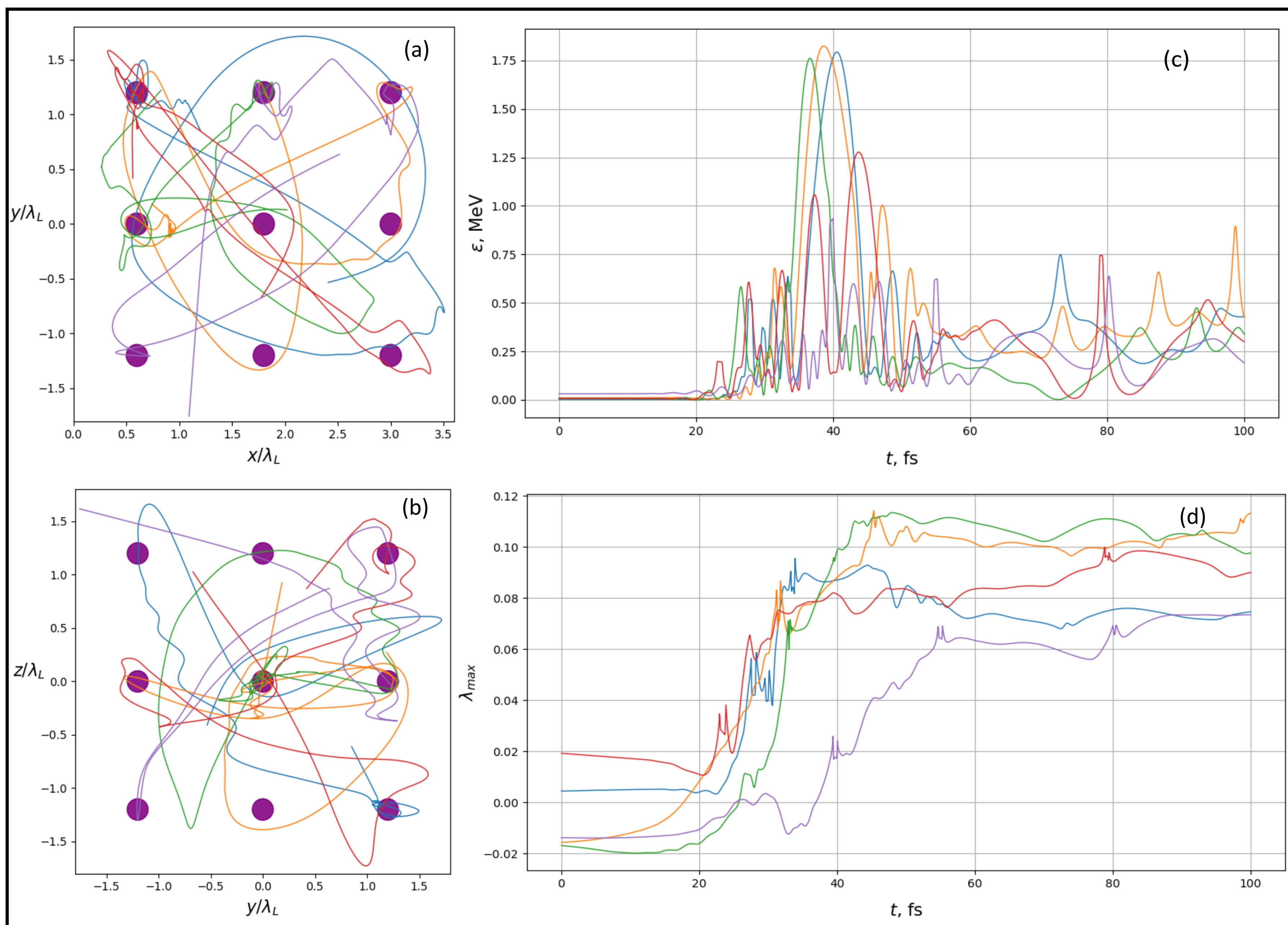


Trajectories of several hot electrons in the plane of polarization and transverse plane in the PIC simulation

To approximate the quasi-static Coulomb field in a test particle the method we use

$$\mathbf{E}^C(\mathbf{r}) = E_{Q0}\frac{m_e c\omega_L}{e}\begin{cases}0, & |\mathbf{R}|\le d/2-l_s,\\ \left(1-\frac{d}{2l_s}+\frac{|\mathbf{R}|}{l_s}\right)\frac{\mathbf{R}}{|\mathbf{R}|}, & d/2-l_s<|\mathbf{R}|\le d/2,\\ \frac{d^2\mathbf{R}}{4|\mathbf{R}|^3}, & |\mathbf{R}|>d/2,\end{cases}$$

where $E_{Q0}/E_L = 2$ was obtain from PIC date



Test particles method

To confirm the stochastic nature of electrons, in such complex quasi-static fields, the test particlemethod was used. The maximum Lyapunov exponent for several electrons was estimated and it takes positive values. Then the motion of these electrons is stochastic.

Trajectories of several electrons in the plane of polarization (a), in transverse plane (b), dependence of the energy of these electrons on time (c) and the maximum Lyapunov exponent for these electrons (d) in the test particles simulation.

Conclusion

1) In this work, the characteristics of the laser pulse were optimized with respect to the number of hot electrons, assuming that the laser pulse energy is constant.

2) An explanation is given of the generation of hot particles (with energies significantly exceeding the ponderomotive energy) as a result of their stochastic walk in complex laser-plasma fields using the method of test particles and the theory of Lyapunov exponents.

3) The role of the plateau in the energy distribution of particles was determined; the energy content of particles from this region dominates over the energy content of the group of super-pondermotive electrons.

4) It is the particles from the plateau region that will determine the characteristics of inverse bremsstrahlung radiation of the cluster plasma.