Ion acceleration in plasmas

Lecture 7. Ion acceleration in clusters

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Cluster is a form of intermediate matter between molecules and bulk solids.

Light-induced processes in clusters can lead to photo-fragmentation and Coulombic fusion, producing atom and ion fragments with a few electronvolts (eV) of energy.

**Recent studies** of the photoionization of atomic clusters with high intensity (>10^{16} W cm^{-2}) femtosecond laser pulses have shown that these interactions can be far more energetic - excitation of large atomic clusters can produce a superheated microplasma that ejects ions with kinetic energies up to 1 MeV. Ditmire et. al., *Nature* **386**, 54 (1997).
Sub-wavelength clusters provide another possibility for efficient ion acceleration. The qualitative picture of ion acceleration in such clusters depends on the strength of the laser field and the cluster radius. Theoretical analysis of this phenomenon can be made with the use of relevant simplifying assumptions that clusters are much smaller than the laser wavelength and that the electron plasma frequency inside the cluster is considerably greater than the laser frequency (thus, overdense plasma).
Introduction: Ion acceleration in clusters

Coulomb explosion
- for small, low-Z clusters
- laser field extracts electrons from the cluster
- charged sphere expands isotropically

Hydrodynamic explosion
- for large, high-Z clusters
- electrons trapped inside the cluster form
- a spherical nanoplasma
- hydrodynamic isotropic explosion
Coulomb explosion in small clusters

Considering a uniform spherical cluster with ion density \( n_{i0} \) in a uniform static electric field \( E_0 \).

The field extracts electrons from the cluster, making the cluster positively charged. If all the electrons are extracted, the cluster becomes a uniform ion sphere with the total charge \( N_i Z_e \), where \( N_i = (4/3) \pi R_0^3 n_{i0} \) is the total number of ions in the cluster and \( R_0 \) is cluster radius.

In this case, the electric field created by the cluster increases from zero at the center to

\[
E_{\text{max}} = N_i Z_e 4 \pi \epsilon_0 R_0^2 = n_{i0} R_0 Z_e / 3 \epsilon_0
\]

at the cluster edge and then decreases radially outside the cluster.
Coulomb explosion in small clusters

The external field can extract all the electrons only if $E_0 > E_{\text{max}}$. In this regime, electrons do not affect dynamics of the ion explosion. The ions are accelerated in the electrostatic field of their own charge, they are receiving the kinetic energy according to their initial position in the cluster from 0 up to the maximum energy.

One may obtain the following relations by considering the transfer of initial potential electrostatic field energy into the kinetic energy of particles.

Coulomb explosion in small clusters

The ion energy distribution function obtained from the simple cluster explosion is proportional to the square root of energy

\[
\frac{dN}{d\varepsilon_i} = \frac{3}{2} \frac{N_i}{\varepsilon_{imax}} \sqrt{\frac{\varepsilon_i}{\varepsilon_{imax}}}
\]

with the maximum (cutoff) energy equal to

\[
\varepsilon_{imax} = \frac{5Z^2e^2}{8\pi\varepsilon_0} \frac{1}{R_0}
\]

The explosion time of small cluster \( (\tau_i = 1/\omega_{pi}) \) is typically much longer than the laser period.

Coulomb explosion in small clusters

This feature of increasing ion number with energy, i.e., of a relatively high average ion energy produced in clusters, attracts the attention due to the possibility of quite efficient neutron production. The latter was demonstrated by numerous experiments, for example with deuterium or deuterated methane clusters.

A typical diameter of those clusters produced in gas jets is several nm, the maximum energy of accelerated ions in the experiments is about 10 keV. The laser pulse intensity used in those experiments is around $10^{17}$ W cm$^{-2}$ and the pulse duration is 40 fs.

Ion dynamics in larger clusters

In small clusters with diameters of a few tens of nanometers, which is of the order of the hot electron Debye length, the Coulomb ion repulsion is the dominant mechanism.

In this case, energies of MeV per nucleon were never observed as their size is considerably limited by the laser field strength. In addition, small clusters are much more sensitive to the laser prepulse and can be easily destroyed before the peak of the laser pulse.

Ion dynamics in larger clusters

Larger clusters with diameters in the 100 nm range are expanding under the pressure of hot electrons, which cannot leave the droplet because of its very high electric charge. Moreover, the ionization is very inhomogeneous - atoms in the outer layer of a thickness about the skin depth (10 nm) are ionized by the laser electric field to a high degree, while atoms in the inner part of the target can be ionized only by electron collisions, which are very rare for high intensity laser pulses. Therefore, it appears that the size of clusters and a high laser pulse contrast are the crucial parameters for efficient ion acceleration.
Ion dynamics in larger clusters

The self-similar expansion of finite-size non-quasineutral plasmas into vacuum, is the case of homogeneous larger cluster. The problem is solved in the planar, cylindrical and spherical geometries ($\nu = 1, 2, 3$) by the set of one dimensional hydrodynamic equations for electron, ion densities (continuity equations) and momentum, Poisson equation, and, instead of the energy equation, a polytropic law is used for the electron temperature evolution

$$T_e(t)/T_{e0} = [n_e(t,0)/n_e(0,0)]^{-\gamma},$$

where $\gamma = 4/3$ (the adiabatic case of ideal electron gas). Here, important parameters are the ratio of cluster radius $R_0$ and Debye length which is kept constant during the

$$\Lambda_s = \frac{R_0}{\lambda_{D0}} = \frac{R(t)}{\lambda_D(t)}.$$
Ion dynamics in larger clusters

We also need to take into account the small but crucial factor $\mu_e = Z \ m_e / m_i \ll 1$ (electron-to-ion mass-over-charge ratio) as the familiar Boltzmann relation cannot be applied for spherical geometry ($\nu = 3$).

The most important output of the self-similar solution is the maximum ion energy $\varepsilon_{imax}$ for ions at the vacuum boundary in the form

$$
\varepsilon_{imax} = \varepsilon_0 \ \xi_f^2,
$$

$$
\varepsilon_0 = 2ZT_{e0}/\nu(\gamma - 1),
$$

where $\varepsilon_0$ is the characteristic energy for ion at infinite time given for the case of instantaneous heating $\gamma > 1$ ($t_L \ll R_0/c_{s0}$, where $t_L$ is the laser pulse length and $c_{s0}$ ion-acoustic velocity).
Ion dynamics in larger clusters

In spherical geometry ($\nu = 3$), the asymptotic behavior of $\xi_f$ with respect to $\Lambda_s$ is analytically derived in the limits $\Lambda_s \ll \mu_s^{-1/2}$ and $\Lambda_s \gg \mu_s^{-1/2}$ as follows

$$
\xi_f^2 = \begin{cases} 
\xi_{fA}^2 = W\left[\frac{\pi^{1/3} \Lambda_s^{4/3}}{(2\mu_e)}\right]/2, & \Lambda_s \ll \mu_e^{-1}, \\
\xi_{fB}^2 = W\left[\Lambda_s^{2}/2\right], & \Lambda_s \gg \mu_e^{-1},
\end{cases}
$$

where $W(x)$ is called the Lambert function defined as the inverse of the function $x(W) = W \exp(W)$. 

Ion dynamics in larger clusters

Asymptotically, \( W(x) \approx x \) for \( x \ll 1 \) and \( W(x) \approx \ln(x/\ln(x)) \) for \( x \gg 1 \). An approximate value of \( \xi_f \) for arbitrary \( \Lambda_s \) is

\[
\xi_f \approx \left( \xi_{fA}^6 + \xi_{fB}^6 \right)^{1/6}, \quad 0 < \Lambda_s < \infty.
\]

The second important output of the self-similar solution is the energy spectrum of ions

\[
\frac{dN}{d\epsilon_i} = \frac{n_{i0}}{\epsilon_0} \left( \frac{\epsilon_i}{\epsilon_0} \right)^{\nu/2-1} \left[ \exp \left( -\frac{\epsilon_i}{\epsilon_0} \right) + \frac{2\nu}{\Lambda_s^2} \right], \quad \epsilon_i \leq \epsilon_{imax}.
\]

In the limit of \( \Lambda_s \to 0 \), \( dN/d\epsilon_i \propto \sqrt{\epsilon_i/\epsilon_0} \) is the Coulomb explosion spectrum, whereas for \( \Lambda_s \to 0 \), \( dN/d\epsilon_i \propto \sqrt{\epsilon_i/\epsilon_0} \exp(-\epsilon_i/\epsilon_0) \) is the ambipolar expansion type of spectra.
Ion dynamics in larger clusters

In reality, the larger clusters are usually composed of several ion species which makes the situation more complicated as the energy spectra of ions are the combination of Coulomb-like and ambipolar-like expansion of spectra. In this case, there is a solution for a particular case of homogeneously distributed impurity ions. This solution accompanied by numerical simulations demonstrates that the formation of a monoenergetic light ion bunch at the maximum energy of the spectra takes place when the factor expressing the Coulomb-like explosion is larger than the factor expressing ambipolar-like explosion, that is, for $\Lambda_s < 5$. 
Thus, in multispecies medium-sized clusters, the light ions are running ahead of heavier ions and, additionally, in the spectra described earlier, the high energy peak is formed.

Clusters are usually spherical targets with a diameter much lower than the laser wavelength.
A sufficiently intense laser wave can expel a relatively large fraction or even all electrons from the cluster. If all electrons are extracted, the cluster expands only under the action of Coulomb forces. This mechanism of ion acceleration results in the energy distribution function proportional to the square root of ion kinetic energy, while the number of ions is exponentially decreasing with their velocity in the TNSA mechanism using thin foils. Thus, the Coulomb explosion gives relatively high average ion energy compared to their maximum (cutoff) energy in the energy spectra.
Ion dynamics in larger clusters

In larger clusters, all electrons cannot leave the target because of very high restoring forces due to their high electric charge. In this case, the ion energy spectrum is composed of two parts which comprise Coulomb-like explosion and ambipolar-like expansion. In multispecies clusters, if the factor expressing Coulomb-like explosion is sufficiently large, i.e. the ratio of the cluster radius and the hot electron Debye length is below 5, a substantial part of light ions forms a monoenergetic light ion bunch at the maximum energy in the spectrum.
Ion dynamics in larger clusters

It is clear that clusters provide alternative possibility for efficient ion acceleration. Although ion energies obtained experimentally using clusters are far below maximum energies of ions accelerated in solid targets, the advantage of clusters is in a relatively high average energy of accelerated ions. As it is possible now to improve laser pulse contrast by recently developed techniques mentioned above to prevent undesirable cluster heating before the interaction with the main laser pulse, larger clusters could be efficiently used in experiments with relativistically intense laser beams, and thus higher ion energies are expected to be measured.
Experiment

High Energy Ions produced in explosions of superheated atomic clusters

(a) Experimental Setup for measuring ion energies of exploding cluster.

(b) Ion Energy Spectrum

Observation of Nuclear Fusion from the Explosions of Deuterium Clusters heated with compact, high repetition-rate, table-top laser – achieved an efficiency of about $10^5$ fusion neutrons per joule of incident laser energy, which approaches the efficiency of large-scale laser-driven fusion experiments.

Deuterium cluster fusion experiment

Problems

Q7.1. True or False. Clusters can be produced by gas expansion at low pressure (and high temperature).
A7.1. False.

Q7.2. Define the range of cluster size!
A7.2. 10 nm.

Q7.3. Why clusters are more efficient for coupling laser energy?
A7.3. High local density in clusters.

Q7.4. Briefly define the Coulomb explosion of cluster!
A7.4. When a cluster target is irradiated by an intense laser pulse and the ponderomotive pressure of the laser light blows away the electrons, the repelling force of an uncompensated electric charge of positive ions causes the cluster Coulomb explosion.
Q7.5. In the case of a multispecies cluster with a relatively small number of the negative ions, the Coulomb explosion leads to the positive acceleration and negative ions are accelerated by the same electric field. Why their acceleration occurs in the opposite direction with respect to the positive ion motion.

A7.5. Electric field formed by the positively charged component accelerates the negative ions inward.

Q7.6. The characteristic energy of ions in exploded cluster depends on laser intensity and Coulomb energy of the target. True or False?

A7.6. False. It depends on the Coulomb energy of the target but is independent of laser intensity.

Q7.7. When hydrodynamic explosion becomes the dominant mechanism in cluster?

A7.7. When the size of a cluster (diameter of cluster) is much longer than the hot electron Debye length.
Problems

Q7.8. True or False. Ionization is inhomogeneous in large cluster due to laser fields.
A7.8. True.

Q7.9. True or False. In the Coulomb explosion mechanism of ion acceleration, the energy distribution function is proportional to the inverse square root of ion velocity, in contrast to the TNSA mechanism in thin foils where the number of ions is exponentially increasing with their velocity.

Q7.10. Why cluster targets may be better alternative of ion acceleration in comparison to ion acceleration from solid targets?
A7.10. Relatively high average energy of accelerated ions.
References


