Plasma generated from collision of cluster beams

B. M. Smirnov

Institute for High Temperatures, 127412 Moscow, Russia

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Processes are analyzed in the course of production of a microplasma as a result of collision of two dense cluster beams. In reality, this microplasma is characterized by the lifetime of ~ 1 ns, by a size ~ 0.01 cm, by the number density of electrons $\sim 10^{20}\,\mathrm{cm}^{-3}$, by the electron temperature of several tens of eV, and by a charge of its multicharged ions up to $z = 10$. Under contemporary conditions, the laser method allows one to create a hot microplasma with more high electron temperature and charge of atomic ions.

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Introduction. A convenient method of generation of a hot microplasma consists in irradiation a cluster beam by a femtosecond laser pulse of a high intensity, so that the electric field strength of the laser field exceeds that inside the hydrogen atom by several orders of magnitude. As a result of the absorption process, clusters are excited by taking the energy of an electromagnet wave. The subsequent expansion of an excited cluster matter during times 0.1–1 ps leads to formation a more or less uniform microplasma that can be used as a source of X-ray radiation, neutrons and fast multicharged ions, and these processes proceed during an expansion time of this uniform plasma (~ 1 ns) [1–3]. Though excited multicharged ions, which are responsible for X-ray radiation of this plasma, can be formed on the first stage of cluster excitation, generation of X-ray radiation proceeds just in an uniform microplasma.

We below consider an alternative method of creation of such a microplasma that results from collision of two intense cluster beams. Collision of two clusters which move towards to each other or collisions of a cluster with individual nuclei lead to transformation of the kinetic energy of nuclei in cluster beams into the energy of excitation of a forming microplasma. Our goal is to analyze the processes which proceed in the course of formation of this microplasma and to estimate the parameters of the plasma.

Cluster parameters in colliding cluster beams. A general scheme of this process corresponds to almost frontal collision of two dense cluster beams after their generation. As a result, a microplasma is formed in the region of collision of cluster beams, and the energy of this microplasma is taken from the kinetic energy of colliding beams. Because this process requires a high intensity and small duration time for colliding beams, we will be guided by the pulse scheme of cluster generation [4]. Taking an example of tungsten clusters, we use the parameters of clusters in a beam evaluated for this scheme. These parameters for the tungsten case are as follows. A typical number of cluster atoms is $n \sim 10^6$, the number density of bound atoms in clusters is $N_b \sim 4 \cdot 10^{19}\,\mathrm{cm}^{-3}$, and a radius of a cluster beam is $40\,\mu$. Note that the number density of bound atoms corresponds to the number density of multicharged ions in a forming microplasma.

On a certain stage of cluster generation, clusters are charged by an electron beam. A charge of an individual cluster is restricted by its strength, and the Rayleigh instability threshold gives the maximum cluster charge [5, 6] $Z_{cr} \approx (5Ar/e^2)^{1/2}$, where A is the specific cluster surface energy, the cluster radius r is expressed through the Wigner-Seits radius r_W as $r = r_W n^{1/3}$. From this formula we have for a tungsten cluster of an indicated size ($A = 4.7$ eV, $r_W = 1.6$ Å [7]) $Z_{cr}/n \approx 2 \cdot 10^{-3}$. It is necessary to account for a decrease of the reduced cluster strength due to cluster excitation by an electron beam in the course of its ionization and also its increase if a cluster is broken in parts by electron impact, so that these effects are mutually cancelled. We take below $Z/n = 1 \cdot 10^{-3}$ for the case under consideration.

On the last stage of cluster generation, clusters are accelerated in an electric field. We assume the pulse electric potential in which clusters are accelerated to be equal to 1 MV and 10 MV in two considering examples, and these values are available for contemporary pulse technique. This corresponds to the energy per nucleus 1 keV and 10 keV respectively, and this corresponds to cluster velocities of $3 \cdot 10^6$ cm/s and $1 \cdot 10^7$ cm/s. For the pulse method of cluster generation [4] when clusters are formed from a drop of radius $10\,\mu$ and the final radius of a generated cluster beam is $40\,\mu$, the total energy transmitted to clusters is 0.02 J and 0.2 J correspondingly.

Later collisions of clusters and collisions of clusters with free ions lead to formation of a microplasma, so that a typical nucleus charge in this microplasma is $z \sim 10$, and typical plasma temperature is several tens of eV.

Processes of collision of cluster beams and parameters of microplasma. As a result of collision of two cluster beams,the kinetic energy is converted in excitation of the electron component, and a hot plasma is formed similar to that resulted from excitation of a cluster beam by a femtosecond laser pulse [1 − 3]. In this case during collision of two clusters atoms of one cluster penetrates inside another one and are decelerated there by interaction with the electron component. As a result, nuclei almost stop, and The excitation energy of the electron subsystem is equal to the initial kinetic energy of nuclei. Considering almost frontal collisions of cluster beams with a small angle between them, we obtain the following criterion for the beam length L in order each cluster would partake in collision

$$N_{cl}\sigma L \geq 1, \tag{1}$$

Here $\sigma = 4\pi r_W^2 n^{2/3}$ is the cross section of collision of two identical clusters, and r_W is the Wigner-Seits radius of clusters. From this we find the beam length

$$L \geq \frac{n^{1/3}}{4\pi r_W^2 N_b} \tag{2}$$

and for the above parameters ($N_b \sim 1 \cdot 10^{19}\,\mathrm{cm}^{-3}$, $r_W \approx 1.6\,\text{Å}$) the criterion (2) gives $L \geq 30\mu m$. This corresponds to a beam size under a pulse method [4] of its generation and gives the collision time of $\tau = L/v \approx 1ns$, that is also a typical lifetime of a forming microplasma which occupies a region of a size $\sim L$ during this time.

We now consider the character of transformation of the cluster kinetic energy into the excitation energy of a forming microplasma. According to an experience in study of cluster collision with a solid surface [8 − 13], during this collision cluster nuclei penetrate into a solid and then under pressure of a cluster shock, a shockwave is forming at some distance from the solid surface, so that transformation of the kinetic energy of cluster beams proceeds to a greater extent through a shock wave. In the case of cluster collisions this mechanism does not hold true because of their small size, and another mechanism of this process consists in excitation of the electron subsystem by moving nuclei, including collective effects, as plasma oscillations, and we consider this mechanism for two limiting cases taking into account that a typical nuclear velocity is small compared to typical electron velocities. Indeed, if a nucleus is moving with a low velocity inside an electron subsystem that is found in the ground state, a small part of electrons can partake in transitions, because the transition with a small change of the electron momentum are prohibited for a most part of electrons. If the electron subsystem is excited, this prohibition does not act, and transformation of the nucleus energy proceeds more effective.

For the ground state of the electron subsystem we consider the model of a dense degenerated electron gas, when electrons are located in a Fermi sphere in a space of electron momenta. Since the nucleus velocity

$$v \ll v_F \tag{3}$$

where v_F is the electron velocity on the Fermi surface, only electrons near the Fermi surface on a distance from it $\sim v$ can partake in transitions. This gives for the deceleration rate [14, 15]

$$-\frac{dE}{dx} = \frac{2z\hbar v}{3\pi a_o^2}\left[\ln\left(\frac{4}{\alpha}\right) - 3 + 3\alpha\ln\frac{4}{\alpha} - \frac{11}{2}\alpha\right] = C(\alpha)\frac{z\hbar v}{a_o^2}, \quad \alpha = \frac{v}{\pi v_F}. \tag{4}$$

Here a small parameter of this expansion is $\alpha \approx v/\pi v_F$, a_o is the Bohr radius, and z is the effective charge of a nucleus when it is moving with a velocity v inside the cluster.

Considering cluster electrons as a degenerate electron gas, we have the Fermi velocity for these electrons

$$v_F = \frac{\hbar}{m_e}(3\pi^2 N_e)^{1/3} = \frac{\hbar}{m_e}\left(3\pi^2\frac{z\rho}{m}\right)^{1/3} = = \frac{\hbar}{m_e r_W}\left(\frac{9\pi z}{4}\right)^{1/3}, \tag{5}$$

where N_e is the electron number density, z is the nucleus charge in a degenerated electron gas, ρ is the tungsten density, and m is the atom mass. The electron shell of a tungsten atoms is $5d^4 6s^2$, and we assume that electrons of these shells can form a degenerate electron gas, i.e. $z = 6$. This gives $v_F = 1.2e^2/\hbar$ for the tungsten case, and $\alpha = 0.004$, $\alpha = 0.012$ for the tungsten nucleus energies 1 keV and 10 keV correspondingly. For these cases we have $C(\alpha) = 0.86$ and $C(\alpha) = 0.60$. The the mean free path of a nucleus inside the cluster with respect of its deceleration is according to formula (4)

$$\lambda = \frac{Ea_o^2}{z\hbar v C(\alpha)}, \tag{6}$$

and for the tungsten cases under consideration we have $\lambda = 500a_o$ and $\lambda = 200a_o$. In reality excitation of the electron subsystem accelerates the excitation process, and hence these values are overstating ones.

In the other limiting case, when final channels for electron transition are open, the deceleration rate for a moving nucleus with respect to excitation of electrons is given by [16]

$$-\frac{dE}{dt} = N_e v \cdot \frac{4\pi z e^4}{m_e v^2} \ln \Lambda, \qquad (7)$$

where the Coulomb logarithm is $\ln \Lambda = \ln(p_{\max}/p_{\min})$, $p_{\max} = m_e v$ is the maximum momentum transferring to a scattered electron, $p_{\min}$ is its minimum value that is determined by the structure of the electron subsystem, and we take for definiteness $\ln \Lambda \approx 5 \div 10$. From this we have for the nucleus mean free path with respect to interaction with an electron subsystem

$$\lambda = \frac{E \cdot m_e v^2 r_W^3}{3z^2 e^4 \ln \Lambda} \qquad (8)$$

and for the parameters of an example under consideration we obtain $\lambda \ll a_o$. In reality, we have an intermediate case between these two limiting ones. Indeed, if we start from the ground state of the electron subsystem, the rate of excitation of the electron subsystem increases sharply in the course of an increase of the degree of its excitation.

Thus, the transformation of the kinetic energy of clusters and collision of two cluster beams results from mutual penetration of atomic cores of one cluster inside another cluster, and these cores are decelerates by excitation of the electron subsystem. Because the deceleration process is the same in the case of an individual atom, transformation of the kinetic energy proceeds also in collisions of individual atoms and atomic ions with clusters and their fragments before Coulomb explosion of excited clusters. This leads to effective conversion of the initial kinetic energy of cluster beams into the energy of a forming microplasma.

We now consider the properties of this microplasma from another standpoint. Various processes leads to establishment of an equilibrium, so that a forming microplasma consists of electrons and multicharged ions. Assuming the ionization equilibrium to be fulfilled, we find the electron temperature T_e at which the equilibrium constant is

$$K(T) = \frac{1}{N_e} \left(\frac{m_e T_e}{2\pi \hbar^2} \right)^{3/2} \exp\left(-\frac{J_z}{T_e} \right), \qquad (9)$$

where J_z is the ionization potential for an atomic ion of a charge z. Taking $z \approx 6$, we obtain that the ionization equilibrium takes place at $J_z/T_e \approx 12$. From this we have that at typical temperatures in the range $T_e = 20 - 40$ eV ionization takes place for ions with the ionization potential $J_z \approx 200 - 500$ eV that corresponds to $z = 7 \div 12$. Note that the kinetic energy of plasma electrons and ions is in the range $150 - 300$ eV in these cases, i.e. a significant part of the initial cluster energy is consumed on ionization of atoms and their ions.

Microplasma from cluster collisions and cluster laser plasma. The properties of this microplasma are similar to those obtained by excitation of a cluster beam by an ultrashort and superpower laser pulse. The lifetime of the plasma resulted of collision of two clusters is $\sim r_W n^{1/3}/v \sim 5 \cdot 10^{-13}$ s, and during this time a dense microplasma is formed inside a region of cluster collision with a the number density of electrons of $N_e \sim 10^{24} cm^{-3}$, and then this plasma expands and is characterized by the electron number density of $10^{19} - 10^{20}$ cm^{-3}. The latter plasma lives during a time of ~ 1 ns. The electron temperature of this microplasma is of several tens of eV, and a charge of multicharged ions of this plasma is below $z = 10$. These parameters are restricted by the kinetic energy of nuclei in an incident cluster beams that we take to be 1 keV per nucleus. This value can be increased by a decrease of a size of clusters in a beam and by an increase of the kinetic energy of clusters that is determined by an experimental technique and can be raise in the course of improvement of the experimental technique.

As for a microplasma formed as a result of irradiation of a cluster beam by a femtosecond laser pulse, its parameters are better though both microplasmas have approximately the same lifetime ($\sim$ 1 ns) on the last stage of its evolution when each microplasma is almost uniform. Indeed, the temperature of the cluster-laser plasma is $0.1 - 1$ keV, and the charge of multicharged ions of this plasma can be $z \approx 30$ (for example, [17–19]).

Thus, under contemporary state of the experimental technique, parameters of the microplasma resulted from collision of two cluster beams yield to those of a laser-cluster plasma. In spite of this, the alternative case of creation of a hot nanosecond microplasma to be worthy of notice since the development of this method can give new results for this microplasma.

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