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INTERACTION OF LASER RADIATION WITH MATTER

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Coulomb explosion of deuterium clusters in a magnetic trap and generation of neutrons

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***Abstract*. A new method is proposed for injecting hot ions into a magnetic trap, which is based on the Coulomb explosion of clusters ionised by radiation from a high-power femtosecond laser. The parameters of the trap required for the confinement of the hot plasma produced after the explosion of deuterium clusters are estimated. It is shown that the neutron yield in the $d-d$ reaction in the trap can substantially exceed this yield directly in the laser beam focus.**

Keywords: *clusters, laser radiation, magnetic trap.*

1. It was shown recently [1, 2] that the hot plasma was produced with the ion energy $\varepsilon \simeq 2.5$ keV after irradiation of deuterium clusters by a high-power femtosecond laser. Also, approximately 10^4 neutrons were generated in the $d-d$ reaction per laser radiation pulse. Because such a low neutron yield does not assume the possibility of any practical applications of this effect, it is desirable to find the method for the confinement of the hot plasma appearing after the Coulomb explosion of clusters in the laser focus. One of these methods can be the plasma confinement in a magnetic tap during the time τ between laser pulses. This time for modern femtosecond lasers can be $\sim 10^{-3}$ s or even shorter. If the plasma confinement time in the trap is comparable with the time between laser pulses, it is possible to create a source of thermonuclear neutrons.

2. The maximum energy of deuterium ions after the Coulomb explosion is achieved when all the electrons leave a cluster during the interaction with laser radiation. This is possible if the pondermotive energy of an electron in the laser field exceeds the Coulomb barrier appearing due to the attraction of ions

$$U_\mathrm{p} = \frac{(eE_0 \lambdabar)^2}{4mc^2} > U_\mathrm{C} = \frac{Ze^2}{R}, \qquad (1)$$

where Z is the total charge of the cluster; E_0 is the electric-field amplitude of a linearly polarised laser wave; $\lambdabar$ is the wavelength; R is the cluster radius; and m is the electron mass. Let us estimate the cluster radius and the laser beam intensity required to achieve the maximum energy. In the case of complete ionisation of the cluster,

$$Z \simeq N = \frac{4\pi}{3} nR^3, \qquad (2)$$

where n is the concentration of atoms in the cluster and N is their total number. Simple estimates from expressions (1) and (2) give the following values of the cluster radius and the laser field intensity required to generate ~ 2.5-keV ions after the Coulomb explosion

$$R \simeq 35\ \text{Å}, \quad J \simeq 5 \times 10^{16}\ \mathrm{W\ cm^{-2}}. \qquad (3)$$

3. Let us assume that the Coulomb explosion of clusters occurs in a magnetic trap and estimate the parameters of the trap needed for the confinement of the hot plasma with the average ion energy $\varepsilon \simeq 2.5$ keV during the time $\tau \simeq 10^{-3}$ s. After the Coulomb explosion, the plasma occupies a volume that substantially exceeds the volume of the laser focal region. It is known [3] that, to confine a plasma in a magnetic field, the criterion

$$p_\mathrm{D} \ll \frac{H^2}{8\pi} \qquad (4)$$

should be fulfilled, where p_D is the pressure of a deuterium plasma and H is the magnetic field strength. The volume of the focal region of a laser beam in experiments [1, 2] was $V \simeq 10^{-4}$ cm^3 at the average concentration of deuterium ions $n_\mathrm{i} \simeq 10^{19}$ cm^{-3}. We will assume that the radius of the magnetic trap is $r \simeq 1$ cm and its height is $l \simeq 10$ cm. Then, the average ion concentration in the trap is $n_\mathrm{i} \simeq 10^{14}$ cm^{-3} and their total number $N_\mathrm{i} \simeq 10^{15}$. Assuming that the plasma is ideal at the temperature $T \simeq 2.5$ keV, we obtain for the field $H \simeq 10$ kG the ratio

$$\beta = p_\mathrm{D}\left(\frac{H^2}{8\pi}\right)^{-1} \simeq 0.1, \qquad (5)$$

which satisfies criterion (1).

The magnetic trap radius in the direction perpendicular to the magnetic field should exceed the Larmor radius for ions:

$$r > r_\mathrm{L} = \frac{v_\mathrm{i} Mc}{eH}, \qquad (6)$$

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where v_i and M_D are the velocity and mass of deuterium ions, respectively. Condition (6) gives the lower limit for the trap diameter. For the values $T \simeq 2.5$ keV and $H \simeq 10$ kG used above, we obtain

$$r \geqslant 1\,\text{cm} \tag{7}$$

in accordance with our choice of the trap parameters.

4. Consider now the conditions required for the plasma confinement after the Coulomb explosion in a magnetic trap. First of all, the frequency of ion–ion collisions in the trap should be substantially lower than the Larmor frequency

$$\nu_{ii} = \frac{4\pi e^4 n_i L_C}{\sqrt{M}\,T^{3/2}} \ll \nu_L = \frac{eH}{M_D c}, \tag{8}$$

where $L_C \simeq 10$ is the Coulomb logarithm; T is the effective temperature; and $M = M_D/2$ is the reduced mass for the $d-d$ collision. According to (8), for $n_i \simeq 10^{14}$ cm^{-3} and $T \simeq$ 2.5 keV, we have

$$\nu_{ii} \simeq 10^3\ \text{s}^{-1}. \tag{9}$$

At the same time, the Larmor frequency in the field $H \simeq$ 10 kG is $\sim 10^8$ s^{-1}. Therefore, we can expect that the plasma will be 'frozen' in the magnetic field during the required time.

The lifetime of the plasma in the trap can be short if cold neutral atoms are present in it in the period between laser pulses. Then, hot ions are neutralised due to the charge exchange and leave the trap. The number of charge exchanges per unit time is

$$N_e = \sigma_e v_i n_i N_0, \tag{10}$$

where σ_e is the charge exchange cross section and N_0 is the number of neutral atoms in the trap. For ions with the energy of a few kiloelectronvolts, we have $\sigma_e \simeq 10^{-15}$ cm^2 [4, 5]. The number of charge exchanges should be much smaller than the number of ions in the trap. Taking (10) into account, this means that the number of neutral atoms in the trap during the time between pulses should not exceed 10^{11}. This criterion is quite strict. However, we should bear in mind that, together with hot ions, electrons of approximately the same energy ($\sim$ 2.5 keV) come to the trap. They ionise neutral atoms, so that the concentration of the latter can be a few orders of magnitude greater.

The confinement time of the plasma is restricted by the ion drift in the direction perpendicular to the magnetic field. The drift velocity $\boldsymbol{v}_\perp$ is determined by the semiempirical Bohm formula [3]

$$\boldsymbol{v}_\perp = -\frac{c}{16 e n_i H}\nabla_\perp p_D, \tag{11}$$

where $\nabla_\perp p_D$ is the pressure gradient in the plasma in the direction perpendicular to the magnetic field. For the estimate, we assume that

$$|\nabla_\perp p_D| \simeq \eta\,\frac{H\delta H}{4\pi r}, \tag{12}$$

where η is a coefficient independent of the coordinate (in our case, $\eta \simeq 0.1$); δH is the change in the magnetic field between the trap centre and its wall. According to (11), for $\delta H/H \simeq 10^{-3}$, the drift time over the distance of the order of the trap radius ($r \simeq 1$ cm) is approximately 10^{-3} s. Therefore, the relative change in the magnetic field over the trap cross section should be rather small.

5. Clusters are formed in a gas flow issuing from a nozzle [1, 2]. The cluster flow should be irradiated by a laser pulse inside the trap. The two types of traps can be considered: open-ended traps and traps with counter magnetic fields [6]. In the case of open-ended traps, the magnetic field at the trap ends is usually a few times greater than at its centre. In this case, the magnetic field in the plane perpendicular to the magnetic force lines should be sufficiently homogeneous, as follows from estimates presented above. The systems with counter magnetic fields seem more attractive because the magnetic field in them increases in all directions from the trap centre. In this case, it is reasonable to irradiate the cluster flow by a laser beam near the trap centre.

In the case of open-ended traps, the region exists near magnetic mirrors where plasma is absent [7]. The solid angle, within which the plasma is absent, is filled due to Coulomb ion-ion scattering. The value of the solid angle is determined by the mirror ratio

$$R = \frac{H_c}{H}, \tag{13}$$

where H_c is the magnetic field in magnetic mirrors. The number of collisions per unit time, which produce ions with the 'critical' direction of the momentum, is determined by the expression [7]

$$\nu_{ii}^{n} = \frac{4\pi e^4 n_i}{\sqrt{M}\,T^{3/2}}\,\frac{1}{\ln R}. \tag{14}$$

By using (14), we can find the characteristic time between 'critical' collisions. Taking into account that $n_i \simeq 10^{14}$ cm^{-3}, $T \simeq 2.5$ keV, and $R \approx 3$, we obtain the estimate

$$\tau_{ii}^{n} \simeq 10^{-2}\ \text{s},$$

which proves to be greater than the time between laser pulses.

6. Based on the estimates made above, we can make the following conclusions. To achieve the quasi-continuous regime of fusion of 2–3-keV deuterium nuclei in a magnetic trap with appropriate parameters, a femtosecond laser is required which emits $\sim$ 0.1-J pulses with a pulse repetition rate of $\sim 10^3$ Hz and provides an intensity of $\sim J \simeq 5\times10^{16}$ W cm^{-2}.

In our case, the concentration of hot ions in the trap is approximately 10^5 times lower than in the laser beam focus in experiments [1, 2]. However, the confinement time of hot ions can be 10^7 times longer. Therefore, for the same parameters of the laser and the cluster flow, the increase in the neutron yield per pulse by two orders of magnitude can be expected. Moreover, the neutron yield can be increased substantially by increasing the ion energy from 2.5 to 10 keV. This can be achieved by increasing the cluster size up to 70 Å and the laser beam intensity up to 2×10^{17} W cm^{-2}. Simultaneously, the magnetic field strength in the trap should be doubled. The increase in the neutron yield per laser pulse could be achieved by increasing the interaction volume of the laser wave with the deuterium cluster flow.

However, two additional conditions, which should be taken into account, prevent this. First, the wave energy per pulse should exceed the energy carried out by all the electrons and, second, the pulse duration should be lower or comparable with the cluster lifetime in the laser wave field ($\sim 20-30$ fs). Therefore, the increase in the focal spot diameter up to 1 cm will require the increase in the pulse energy up to 10^3 J. Note in conclusion that the method for injecting hot ions can be used not only in open traps but also in tokamaks.

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