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XIII Халықаралық ғылыми конференциясы

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ON THERMALIZATION CHARACTERISTICS OF FAST IONS IN HOT DENSE D^3 H E PLASMA

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Abstract

A hot dense plasma, which is in a completely ionized state, is considered. In fusion processes high-energy particles with energies in 1-14 MeV range appear. On the way to come into thermal equilibrium with environment medium they lose excess energy on thermalization length in corresponding thermalization time. Examining only charged components of fusion products and considering stopping characteristics of ions in hot dense plasma due to Coulomb interaction, the parameters of thermalization length and time in D^{3}He plasma are calculated numerically using iterations procedure.

Introduction

There is a tremendous interest to the behavior of fast ions in hot dense plasmas from the view of many aspects of plasma and controlled fusion research. One of the important descripting parameters is ion's energy exchange with electronic and ionic components of plasma. It plays one of the key roles in controlled fusion process modeling. Confined plasma substance with suitable conditions for launching fusion processes is an environment for fast high energetic fusion products to travel, leaving excess compared to thermal energy for medium heating. Fusion reactions that take place in such plasma produce high-energetic ions with energies from 1 to 14 MeV range. For D^{3}He fuel as well as for other type of fuels in the equilibrium states with Maxwell distribution the main products of the fusion reactions are p(14.68), p(3.02), ^{4}He(3.72), ^{4}He(3.72), ^{4}He(3.72), ^{4}He(3.72) with energies in MeV shown in brackets. Types of fusion reactions in different fuel types one can find in [1].

The energy losses of energetic charged particle inside plasma occur mostly due to Coulomb interaction. As it is determined in [2, 3] close interactions of ions in certain plasma behavior studies still can carry importance, however for our problem they are small enough and can be neglected [4]. In this work we calculate average time (*thermalization time*) passed and distance (*thermalization length*) undertaken by the fast product particles since birth in fusion reaction until thermalization to the average environment plasma temperature. For this case it is assumed that particles do not enter secondary reaction during their travel. Only charged product particles are considered due to estimation of energy loss by Coulomb interaction.

Ions stopping power due to Coulomb interaction

Energy exchange power of high-energetic j ion with plasma's k ion component determined by Coulomb interaction is defined as [4, 5]:

$$\left.\frac{dE_j}{dt}\right|_{j-k} = -\frac{4\pi e^4 \left(Z_j Z_k\right)^2}{\left(2m_k T_k\right)^{1/2}} n_k \Lambda_k \frac{\Psi\left(x_k\right)}{x_k}\ , \qquad (1)$$

where $\Psi(x_k) = erf(x_k) - 2/\pi^{(1/2)}(1+m_k/m_j)x_k exp(-x_k^2)$, и $x_k = \left(\frac{m_k}{m_j}\frac{E_j}{T_k}\right)^{1/2}$.

Here Λ_k is dimensionless Coulomb logarithm which value is usually in the range of 10-20, Z_j is the charge number of ion j, Z_k is the charge number of separate plasma's k ion, m_j is the mass of ion j, m_k is the mass of separate k ion, n_k is the number density of plasma k component, T_k is plasma temperature. For fuel mixture of two or more plasma components the energy exchange power should be summed over all components.

The corresponding detailed derivations of the equation can be found in [5]. The approaches in Sivukhin et. al. [4] and in Butler et. al. [5] correspond to pair interaction of ions, which suits to dense plasmas in the Inertially Confinement Fusion devices.

Thermalization length and time correspond to distance and time needed to particle to come to thermal equilibrium with plasma. They are determined by next formulas:

$$l_{therm.} = \int \frac{dE}{\left.\frac{dE}{dx}\right._{total}} \qquad (2)$$

$$t_{therm.} = \int \frac{dE}{\left.\frac{dE}{dt}\right._{total}} \qquad (3)$$

which should be integrated over the interval from current particle energy E_0 to plasma average energy $\frac{3}{2}kT_k$, where k is Boltzmann's constant. Thermal energy corresponds to average kinetic energy of plasma and is determined simply as $\frac{1}{2}m_k\upsilon^2 = \frac{3}{2}kT_k$.

Due to presence of error function part in (1) the analytical solution is complicated. However, one can find numerical results by iteration method. The algorithm is introduced as:

$$E_i - \left(\frac{dE}{dx}_{total}\right)\Delta x = E_{i+1}, \qquad (4)$$

$$E_i - \left(\frac{dE}{dt}_{total}\right)\Delta t = E_{i+1}, \qquad (5)$$

where i denotes step number.

The initial value of iteration is E_0. The iteration step Δx taken in such way that energy is changed slightly fluent with least error. Here we can assume $\Delta x = r_{Debay}$, i.e. equal to Debay radius with enough accuracy. Length-time relation is stated as $\Delta x = \upsilon t$, from where an actual particle velocity can be found by $\upsilon = \sqrt{\frac{2E}{m}}$. Providing the iterations till E_{i+1} becomes equal to $\frac{3}{2}kT_k$, then taking the sum over all iteration steps and multiplying by steps Δx and Δt, finally we obtain, correspondingly, $l_{therm.}$ and $t_{therm.}$.

Numerical calculations

Let us find the values of thermalization length and thermalization time for some of fusion products travelling through plasma in extreme conditions. For numerical calculations of the thermalization parameters we accept state conditions of fuel mixture as n_k=5*10^{23} cm^{-3} (for each component) and plasma's electronic components temperature be equal to average plasma's ionic temperature, i.e. $T_e = \langle T \rangle_{ion}$. These conditions are inherent in dense hot plasma in future fusion device types [6, 7]. The medium plasma is $D\,^3He$ and is in ideal and fully ionized state. Therefore, the energy exchange between high-energetic products of fusion reactions and bulk plasma corresponds to the energy exchange with bare nuclei of fuel and their free electrons.

In result of calculations according to described algorithm we obtain next results for $l_{therm.}$ (Table 1) and for $t_{therm.}$ (Table 2).

Table 1.

Values of $l_{therm.}$ in μm for different energetic fusion reaction products.

<T>$_{ion}$ (keV)	p (14,68 MeV)	p (3,02 MeV)	^4He (3,52 MeV)	^4He (3,67 MeV)	^3He (0,82 MeV)	^3H (0,82 MeV)
10	820 355	34 878	2 979	3 236	238	1 405
20	820 862	35 385	3 066	3 324	300	1 681
30	821 708	36 229	3 201	3 460	376	2 022
40	822 892	37 404	3 367	3 629	476	2 465
50	824 415	38 901	3 563	3 830	619	3 087
100	837 103	50 826	4 718	5 015	1 450	6 669

Table 2.

Values for $t_{therm.}$ in *ps* for different energetic fusion reaction products.

<T>$_{ion}$ (keV)	p (14,68 MeV)	p (3,02 MeV)	^4He (3,52 MeV)	^4He (3,67 MeV)	^3He (0,82 MeV)	^3H (0,82 MeV)
10	20 586.2	1 974.4	313.8	333.3	51.7	265.6
20	20 694.9	2 083.2	338.1	357.6	75.6	364.8
30	20 835.8	2 223.9	369.6	389.3	99.4	465.0
40	21 002.5	2 390.3	407.2	427.1	132.0	601.1
50	21 191.7	2 578.5	453.6	473.8	181.1	803.9
100	22 407.4	3 768.2	687.2	709.8	395.9	1 696.5

Conclusions

As result of calculations of fast ions stopping it was found obviously that the increasing temperature contribute to the increase of thermalization parameters (thermalization length and thermalization time). Charge also affects the stopping as one could see from the results in Table 1 and Table 2 and also Eq.1. Results for particles thermalization parameters in various plasma types can be obtained analogously.

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