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Slowing-down Effect of α Particles in D-T Fusion Ignition*

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Abstract: A three-temperature thermonuclear burn model considering the slowing-down effect of alpha particles is presented, with which the temporal evolution of temperature and particle number density are calculated. Comparison with the description that alpha particles deposit their energy instantaneously, calculation shows that the slowing-down effect of alpha particles delays ignition time, makes the maximum of electron and ion temperatures lower and is more remarkable for lower density conditions.

Key words: alpha particle; energy deposition; slowing-down effect; thermonuclear burn
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1 Introduction

In thermonuclear burn, various fusion reactions occur, releasing a large quantity of charged products and neutrons. While the neutrons escape from optic thin plasma, the charged products deposit their energy into plasma and therefore sustain thermonuclear fusion. Compared with hydrodynamic time scale, the charged particles slow down so fast that considering the charged particles stopping instantaneously is a good approximation in most hydrodynamic process[1]. But in thermonuclear burn, the slowing-down effect of charged particles in plasma should be concerned as its character time is closer to slowing-down time of charged particles.

In this paper, the successive binary collisions theory has been used to describe the slowing-down process of alpha particles in plasma[2, 3]. Based on a three-temperature thermonuclear burn model[4], in which bremsstrahlung, inverse bremsstrahlung and Compton scattering effects have been considered, the thermonuclear burn process of D-T plasma is calculated, and slowing-down effect of alpha particles in ignition is studied.

2 Simulation Model

Assuming that the D-T plasma is uniform, producing alpha-particle isotropically, the time scale of the implosion is far longer than thermonuclear burn time so that the volume of the plasma can be assumed constant during D-T ignition. The electron temperature, ion temperature and radiation temperature are uniform respectively in plasma. There are mainly four thermonuclear reaction channels of D-T:

$$\mathrm{D} + \mathrm{T} \rightarrow \mathrm{n}(14.07\ \mathrm{MeV}) + \alpha(35.2\ \mathrm{MeV}),$$
$$\mathrm{D} + \mathrm{D} \rightarrow {}^{3}\mathrm{He}(0.82\ \mathrm{MeV}) + \mathrm{n}(2.45\ \mathrm{MeV}),$$
$$\mathrm{D} + \mathrm{D} \rightarrow \mathrm{T}(1.01\ \mathrm{MeV}) + \mathrm{p}(3.03\ \mathrm{MeV}),$$
$$\mathrm{D} + {}^{3}\mathrm{He} \rightarrow \alpha(3.6\ \mathrm{MeV}) + \mathrm{p}(14.7\ \mathrm{MeV}).$$

The ion particle number density equations can be written as[4]

$$\frac{\mathrm{d}n_{\mathrm{T}}}{\mathrm{d}t} = R_{\mathrm{DDp}} - R_{\mathrm{DT}} , \tag{1}$$

$$\frac{\mathrm{d}n_{\alpha}}{\mathrm{d}t} = R_{\mathrm{DT}} + R_{\mathrm{D},{}^{3}\mathrm{He}} , \tag{2}$$

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$$\frac{dn_D}{dt} = -R_{DT} - 2(R_{DDn} + R_{DDp}) - R_{D,^3He} \quad , \quad (3)$$

$$\frac{dn_{^3He}}{dt} = R_{DDn} - R_{D,^3He} \quad , \quad (4)$$

$$\frac{dn_p}{dt} = R_{DDp} + R_{D,^3He} \quad . \quad (5)$$

Here n_k is the particle number density of species k ions, k can be one of T, ^{4}He, D, $^{/3}$He, p. R_{ij} is Maxwell averaged volumetric reaction rate between i species and j species, i. e., the number of reactions between i species and j species per unit time and per unit volume is given by

$$R_{ij} = \frac{n_i n_j}{1+\delta_{ij}} \langle \sigma \nu \rangle_{ij} \quad . \quad (6)$$

Where the Kronecker $\delta_{ij} = 1$ if i = j and $\delta_{ij} = 0$ elsewhere. $\langle \sigma\nu \rangle_{ij}$ is Maxwell averaged reactivity of species 'i' and 'j', which is the function of ion temperature.

The electron, ion and photon energy density rate equations are given as

$$\frac{dE_e}{dt} = S_\alpha^e - \left(\frac{dE}{dt}\right)_{ic} - \left(\frac{dE_r}{dt}\right)_b - \frac{dE_C}{dt} \quad , \quad (7)$$

$$\frac{dE_i}{dt} = S_\alpha^i - \left(\frac{dE}{dt}\right)_{ic} , \quad (8)$$

$$\frac{dE_r}{dt} = \left(\frac{dE_r}{dt}\right)_b + \left(\frac{dE_C}{dt}\right) . \quad (9)$$

Where $E_e = (3/2) n_e kT_e$ is the electron energy density and kT_e is the electron temperature. $E_i = (3/2) n_{ion} kT_i$ is the ion energy density and kT_i is the ion temperature. $E_r = \sigma'_\alpha kT_r^4$ is radiation energy density, $\sigma'_\alpha = \pi^2 / [15(\hbar c)^3]$ and kT_r is the effective radiation temperature. S_α^e and S_α^i represents the alpha-particle energy source to electron and ion respectively, $(dE/dt)_{ie}$ represents the ion-electron energy exchange, $(dE_r/dt)_b$ represents the energy loss rate due to bremsstrahlung and inverse bremsstrahlung, dE_C/dt represents the energy loss rate due to Compton scattering. The power density deposited to electrons by alpha particles at time t is

$$S_\alpha^e(t) = \int_{t_0}^{t} \left(-\frac{dE_\alpha(t_1, t)}{dt} \right)_e R_{DT}(t_1) dt_1 \quad . \quad (10)$$

Here $(-dE_\alpha(t_1, t)/dt)_e$ is the energy loss rate of an alpha particle released at time t_1 to electrons at time t. The power density deposited to plasma ions by alpha particles at time t is

$$S_\alpha^i(t) = \int_{t_0}^{t} \left(-\frac{dE_\alpha(t_1, t)}{dt} \right)_i R_{DT}(t_1) dt_1 \quad . \quad (11)$$

Where $(-dE_\alpha(t_1, t)/dt)_i$ is the energy loss rate of an alpha particle released at time t_1 to plasma ions at time t. $(dE/dt)_{ie}$ in Eqs. (7) and (8) represents the energy exchange between all kinds of ions and elections in plasma, while ions and electrons obey Maxwell distributions. It can be written as[6]

$$\left(\frac{dE}{dt}\right)_{ie} = \sum_k \left(\frac{dE}{dt}\right)_{ke} \quad . \quad (12)$$

Where k = T, ^{4}He, D, ^{3}He, p, and

$$\left(\frac{dE}{dt}\right)_{ke} = -4\sqrt{2\pi} n_k n_e (Z_k Z_e e^2)^2 \Lambda_{ke} \cdot \frac{(kT_i - kT_e)}{m_e c^2 m_k c^2} \frac{c}{\left(\frac{kT_i}{m_k c^2} + \frac{kT_e}{m_e c^2}\right)^{3/2}} \quad . \quad (13)$$

Where

$$\Lambda_{ke} = \ln\left(\frac{3/2}{Z_i \sqrt{\pi} (e^2)^{3/2}}\right) - 0.5 \ln n_e + 1.5 \ln kT_e ,$$

c is the speed of light, e is the elementary charge. $(dE_r/dt)_b$ in Eqs. (7) and (9) represents the bremsstrahlung and inverse bremsstrahlung term,

$$\left(\frac{dE_r}{dt}\right)_b = \sum_k \left(\frac{dE_r}{dt}\right)_b^k \quad , \quad (14)$$

where $(dE_r/dt)_b^k$ represents the energy loss of electrons per unit time per unit volume due to the bremsstrahlung and inverse bremsstrahlung[6] caused by ions of species k.

$$\left(\frac{dE_r}{dt}\right)_b^k = 16\sqrt{2\pi} \frac{e^2}{(\hbar c)} \frac{(e^2)^2 c}{(3 m_e c^2)^{3/2}} \cdot Z_k^2 \sqrt{kT_e} n_k n_e \left[1 - \left(\frac{kT_r}{kT_e}\right)^{1.709}\right] . \quad (15)$$

The dE_C/dt in Eqs. (7) and (9) represents the energy loss of electrons per unit time per unit volume due to Compton scattering, it can be written as[5,6],

$$\frac{dE_C}{dt} = \frac{32}{45}(e^2)^2 c\left(\frac{\pi}{m_e c^2 \hbar c}\right)^3 n_e \cdot kT_e\left(1 - \frac{kT_r}{kT_e}\right)(kT_r)^4 \quad . \qquad (16)$$

3 Calculations and Results

D-T thermonuclear burn process has been calculated considering alpha particles slowing down gradually and comparing with the description that alpha particles slow down instantaneously. The initial temperatures of electron, ion and radiation are 3 keV and The initial density of D-T is 300 g/cm^3. Throughout the calculation, the energy conservation and charge conservation are satisfied.

The temporal evolutions of electron, ion and radiation temperature are shown in Fig. 1, which are calculated considering the alpha particles slowing down gradually. Fig. 1 shows that temperatures of electron, ion and radiation are consistent at the start, spring up separately at $t \approx 0.03$ ns and approach to consistence after $t \approx 0.2$ ns. Fig. 1 also shows that the ion temperature peak is higher and decrease more flatly than that of the electron.

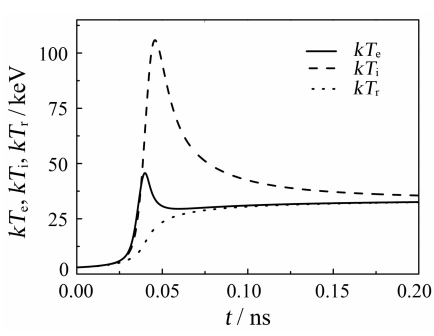

Fig. 1 Time evolution of electron, ion and radiation temperature in thermonuclear burn. k is the Boltzmann constant.

The temporal evolutions of particle number densities of plasma ions in thermonuclear burn are illustrated in Fig. 2. Fig. 2 illustrates that the particle number densities of D and T decrease steeply from 100% to 20% in 0.16 ns. In the end of the burn, the number density of D is a little more than that of T because of tritium breeding in Eq. (3).

The temporal evolution of ion and electron temperature considering the slowing-down process of the alpha particles are compared in Fig. 3 with the description that considering the alpha particles slow down instantaneously. Results in Fig. 3 show that the peaks of ion and electron temperatures are lower about 10 keV than the instantaneous case. The time when the maximum temperatures appear also delay several ps in the gradual case.

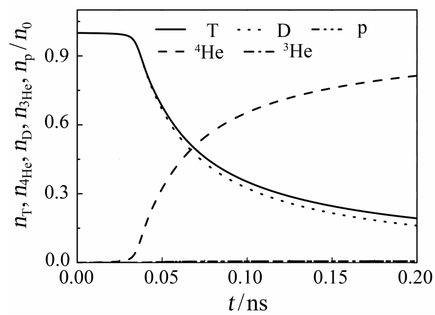

Fig. 2 Temporal evolution of particle number densities of all kinds of ions in thermonuclear burn.

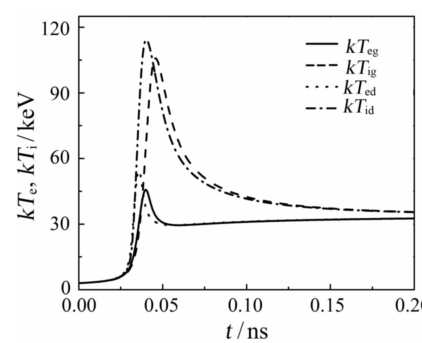

Fig. 3 Comparison of temporal evolution of temperature in thermonuclear burn.

Fig. 4 shows that the difference of the maximum electron temperature in ignition between the instantaneously and gradually stopping descriptions of alpha particles under different initial D-T density conditions.

$$\Delta kT_{epk} = kT_{epkd} - kT_{epkg} \quad ,$$

kT_{epkd} and kT_{epkg} are the maximum electron temperatures assuming the alpha particles deposited their energy instantaneously and gradually respectively. From Fig. 4 it can be seen that $\Delta kT_{epk}/kT_{epkd}$ decreases while the initial D-T density increases. This means that the slowing down effect of the alpha particles become unremarkable under higher densities. The same conclusions can also be obtained for maximum ion temperatures from Fig. 5.

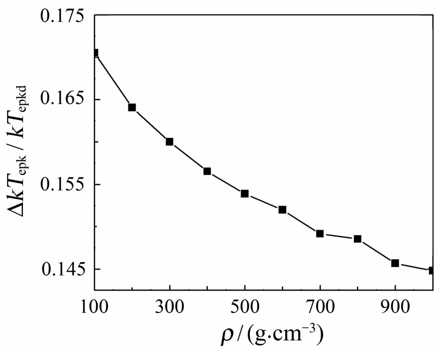

Fig. 4 Difference of the maximum electron temperature between the instantaneously and gradually stopping descriptions of the alpha particles.

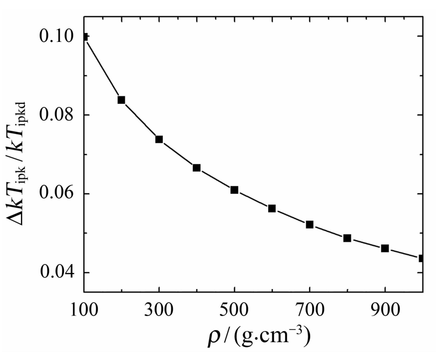

Fig. 5 Difference of the maximum ion temperature between the instantaneously and gradually stopping descriptions of alpha particles.

Compared with the instantaneously and gradually stopping descriptions of the alpha particles, Fig. 6 illustrates difference of the time when the maximum ion and electron temperatures appear under different D-T densities. From Fig. 6 it can be seen that the difference become smaller while the initial D-T density increases. This also means that the effect of the alpha particles is more remarkable under lower D-T densities.

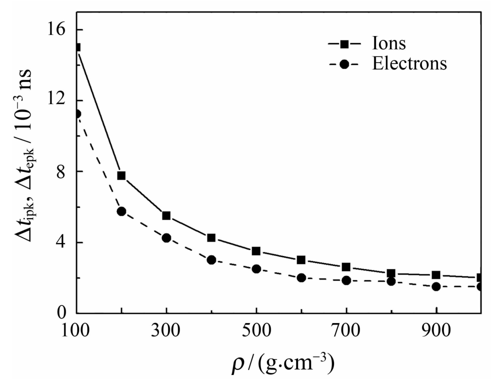

Fig. 6 Compared with the instantaneously and gradually stopping description of alpha particles, the difference of the time at which the electron or ion temperatures are maximum.

In conclusion, after considering the slowing-down process of the alpha particles, the ignition time is delayed, the fronts of the temperature peaks grow slower and the maximum of temperatures are lower than the instantaneous case. The slowing-down effect is more remarkable for lower density conditions.

References:

[1] Atzeni S. Plasma Physics and Controlled Fusion, 1987, **29** (11): 1 535.

[2] Evans F. Phys Fluids, 1973, **16**(7): 1 011.

[3] Sivukhin D V. Rev of Plasma Phys, Consultants Bureu, New York, 1966, **4**: 93.

[4] Eliezer S, Henis Z, Martinez-val J M, *et al.* Phys Lett, 1998, **A243**(5 -6): 311.

[5] Gsponer A, Hurni J-P. Phys Lett, 1999, **A253**(1): 119.

[6] Zhang J, Chang T Q. Fundaments of the Target Physics for Laser Fusion. Beijing: National Defence Industry Press, 2004, 119—126(in Chinese).
(张 钧, 常铁强. 激光核聚变靶物理基础. 北京: 国防工业出版社, 2004, 119—126.)

氘氚聚变点火的 α 粒子的慢化效应*

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摘要：在三温聚变燃烧点模型框架下，对比氘氚聚变燃烧过程中 α 粒子能量逐步沉积与瞬时沉积两种描述下等离子体的温度、离子数密度随时间的变化，针对不同的密度条件做了计算，考察了 α 粒子慢化过程对氘氚聚变点火的影响。发现考虑了 α 粒子的慢化过程后，峰值温度时刻延迟出现，电子和离子的峰值温度都有所降低。在相同的初始温度条件下，α 粒子的慢化效应在较低的密度条件下对点火有更大的影响。

关键词：α 粒子；能量沉积；慢化效应；点火

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