Localization of thermonuclear combustion in a plasma with electronic thermal conductivity

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(Submitted 3 October 1977)
Pis'ma Zh. Eksp. Teor. Fiz. **26**, No. 9, 620–624 (5 November 1977)

It is shown that within the framework of planar geometry, the process of ignition of thermonuclear combustion in a D+T plasma, when account is taken of the electronic thermal conductivity and of the local absorption of the α particles, can be accompanied by localization of the combustion on definite sections of the medium during a finite time interval. The dimensions and amplitudes of the initial temperature perturbations that lead to resonant excitation of the combustion are indicated. The dimension and time scales of the development of the thermonuclear combustion structure are given.

PACS numbers: 52.35.–g, 52.25.Lp

Within the framework of planar geometry and with the medium represented by a model th takes into account the electronic thermal conductivity and the local absorption of the α partic we have considered the singularities of the ignition of thermonuclear combustion (TC) in D+ plasma. It is shown that this process can be accompanied by localization of the combustion definite sections of the medium during a finite time interval, and that its excitation has a resona character and depends on the amplitude and dimension of the initial temperature perturbatio

1. The propagation of a TC wave was investigated in[1-3]. In the present paper we consider t initial stage of the combustion, due to a temperature perturbation of finite amplitude. In the targ used in laser-driven thermonuclear fusion, this perturbation is produced, as shown by compu calculations, by the initial shock wave and by the subsequent heating of the medium in the cou of its almost adiabatic compression.[1,4,5]

We shall neglect the burnout of the DT material and the radiation transport processes, a regard the plasma as a single-temperature ideal and immobile medium. The validity of t assumptions will be verified below.

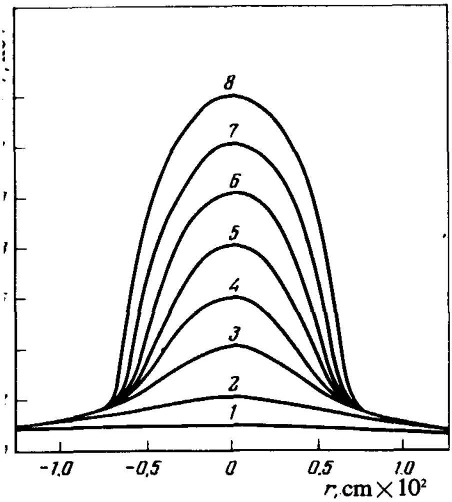
For the reaction cross section $\langle\sigma v\rangle_{DT}$ we use an expression[6] that is valid in the ran $1 \lesssim T \lesssim 30$ keV. For a fully ionized plasma with equal concentrations of D and T, the igniti process is then described by the equation

$$\frac{\partial T}{\partial t}=k_0\frac{\partial}{\partial r}\left(T^{\sigma}\frac{\partial T}{\partial r}\right)+\frac{q_0T^{\beta}}{1+BT^{b}}, \qquad ($$

where T(keV) is the temperature; k_0T^{σ} is the electronic thermal diffusivity coefficie $k_0=8.1\times10^{3}\rho^{-1}$ cm^2 sec^{-1} keV$^{-2.5}$, $\sigma=2.5$; $q_0=4.7\times10^{5}\rho$ sec^{-1}keV$^{-4.2}$, $\beta=5.2$, $B=2.4\times1$ keV$^{-3.6}$, $b=3.6$; ρ(g/cm^3) is the density.

2. The solutions of Eq. (1) with $B\equiv0$ were investigated in[7] and in greater detail in[8]. The investigations had led to formulation of the concepts of the "regime with sharpening" and "flash The former is due to the type of source: if $\beta>1$, then Eq. (1) has solutions in which t temperature of the perturbation increases so rapidly that it becomes infinite within a finite tin

0021-3640/77/2609-0469$00.60



[G. 1. Temperature profiles for the following instants of time: $t=0.0$ sec (1); $t=3.538\times10^{-8}$ sec); $t=3.715\times10^{-8}$ sec (3); $t=3.728\times10^{-8}$ sec (4); $t=3.732\times10^{-8}$ sec (5); $t=3.735\times10^{-8}$ sec); $t=3.737\times10^{-8}$ sec (7); $t=3.738\times10^{-8}$ sec (8).

terval. The latter is connected with the presence of competition between the release of the heat om the source and the spreading of the heat by thermal conductivity. If the spreading of the heat the case of a perturbation with a given dimension Δr_0 and a given temperature T_m is not mpensated for by the source, then its temperature decreases. Combustion is excited in the edium when $\Delta r_0 \geqslant \Delta r_*$,

$$\Delta r_* = \pi\sqrt{\frac{2(\beta+\sigma+1)}{\sigma(\beta-1)}}\sqrt{\frac{k_0}{q_0}}\,T_m^{\frac{\sigma+1-\beta}{2}}, \qquad (2)$$

here Δr_* is the resonance length (RL) and is analogous to the critical dimension in linear ultiplying systems.[7,8] In this case a combustion flash develops immediately and is accompanied a growth of the temperature in the "regime with sharpening." During the flash stage, in the so lled S and LS regimes of combustion ($\beta \geqslant \sigma+1$), a "concave" temperature profile is produced, d as a result the combustion is localized on the RL for a finite time $\Delta t_* \approx (q_0 T_m^{\beta-1})^{-1}$.[7,8] In the LS gime, the half-width of the combustion region decreases with time. In the HS regime $<\beta<\sigma+1$), the temperature profile is "convex" and the dimension of the combustion region creases.[7,8] In the S regime ($\beta=\sigma+1$) this dimension is constant, and the RL, in contrast to the regime, depends only on the properties of the medium and does not depend on the initial rturbation.

3. In the temperature range 1–3 keV, the expression for the source in (1) is close to q_0T. Since $=5.2>3.5=\sigma+1$, this source can lead, in accordance with[7,8], to localization of the combustion er a definite length. At higher temperatures, allowance for the term BT^b in the denominator of e expression for $q(T)$ in (1) leads to a change in the effective value β_{eff} in the expression $T)=q_{\mathrm{eff}}T^{\beta_{\mathrm{eff}}}$. Thus, at $T\approx 5$ keV we have $q(T)\approx q_S T^{\sigma+1}$ with $q_S\approx 5.1\times10^6\rho$ sec^{-1} keV$^{-2.3}$, and at $\gtrsim 5$ keV we have $\beta_{\mathrm{eff}}<\sigma+1$.

These approximations make it possible, using the results of[7,8] to obtain the principal characristics of the TC in the range 1–10 keV, if this combustion is excited by a perturbation with $_0 \geqslant \Delta r_*$. The dimension Δr_{nuc} of the localization region of the TC is given by formula (2):

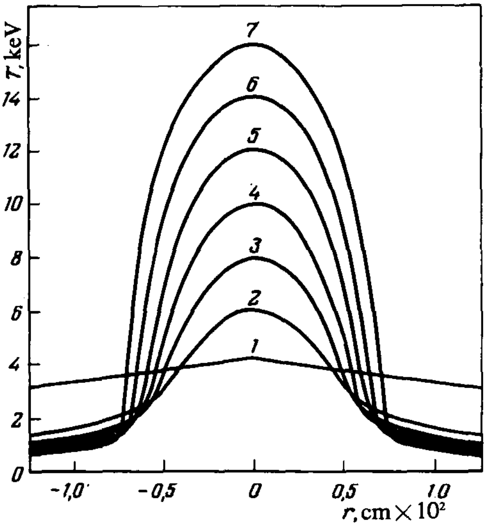


FIG. 2. Temperature profiles for the following instants of time: $t=0.0$ sec (1); $t=3.2\times10^{-10}$ se (2); $t=3.8\times10^{-10}$ sec (3); $t=4.1\times10^{-10}$ sec (4); $t=4.3\times10^{-10}$ sec (5); $t=4.5\times10^{-10}$ sec (6 $t=4.7\times10^{-10}$ sec (7).

$\Delta r_{\text{nuc}} \approx (0.5/\rho T_m^{0.85})$ cm (if the initial amplitude varies in the range $T_m \sim 1$–3 keV). The combu tion is localized during a time $\Delta t_{\text{nuc}} \approx 10^{-6}/\rho T_m^{4.3}$ sec. When temperatures ~ 5 keV are reached i the course of the combustion, the dimension and time of localization of the combustion region a determined by the "S regime": $\Delta r_{\text{nuc}}^{(S)} \approx (0.2/\rho)$ cm and $\Delta t_{\text{nuc}}^{(S)} \approx 8\times10^{-8}/\rho T_m^{2.5}$ sec. With furth increase of the temperature, its profile inside the localization region turns convex and an increas of the combustion region begins at $T > 10$ keV.

Figure 1 shows the results of the numerical solution of Eq. (1), which describes the develo ment of the initial perturbation, specified at the length 0.1 cm and having an amplitude $T_m =$ keV. The density is $\rho = 20$ g/cm³. The flareup region has a dimension $\sim 2.5\times10^{-2}$ cm. The lifetin of the TC structure is $\sim 4\times10^{-8}$ sec, also in agreement with the presented formulas. We note th in as much as ρ is constant, we can replace the independent variables in (1) by $t' = \rho t$ and $r' = \rho$ By the same token, the solutions of (1) become the same for all densities if the length and tir scales are multiplied by a factor K whenever the compression is increased by K.

4. Let us estimate the influence of the processes that are not taken into account in t proposed model.

Comparing the relaxation times Δt_{ei} of the ion and electron temperatures[9] and the α-partic ranges Δr_α[10] with Δt_{nuc} and Δr_{nuc}, we find that the single-temperature approximation and th model of local absorption of the α particles are valid at $T \lesssim 7$ keV. The contribution of the neutror can be disregarded since their range[11] Δr_n is large in comparison with Δr_{nuc}. Using the solutio obtained in[6], we find that half of the thermonuclear fuel burns out within the tim $\Delta t_{0.5} \approx (8.4\times10^{-24}/\rho\langle\sigma v\rangle_{\text{DT}})$ sec. From a comparison of the expression with Δt_{nuc} it follows th the development of the burning formation can be considered without allowance for the burnou All these estimates are independent of the density, because Δt_{ei} and $\Delta t_{0.5}$, Δr_α and Δr_n as well Δt_{nuc} and Δr_{nuc}, are proportional to ρ^{-1}.

Allowance for the volume radiation is essential if the γ-quantum range Δr_{γ}[9] exceeds the imension of the burning region. Calculation shows that in reasonable temperature ranges (not wer that 1 keV) and compression-rate ranges (not larger than by a factor of 10^4) the burning rmation is transparent. The emission is equivalent to adding to (1) a drain $g(T)=g_0T^{0.5}$, where $=2.2\times 10^{8}\rho$ sec^{-1} keV$^{0.5}$.[9] For $T\gtrsim 3.7$ keV, $g(T)<q(T)$ independently of the density, since both q nd g are proportional to ρ. If the TC structure begins to be formed at temperatures 4 keV, then e volume emission can no longer extinguish it. Figure 2 shows the results of the calculation with llowance for the losses for volume radiation. The initial amplitude of the perturbation is ≈ 4 keV, $r_0\approx 0.1$ cm, and $\rho=20$ g/cm^3.

On the other hand, there exists a density range in which the burning region is optically dense, nd the radiant thermal conductivity is small compared with the electronic one. At $T\lesssim 7$ keV this mounts to compressions by a factor $\sim 10^6$ relative to the density of DT ice. In this case there is no olume emission.

The expansion time of the burning region can be estimated at $\Delta t_s\approx \Delta r_{\text{nuc}}/c_s$, where $\approx 2\times 10^7 T^{0.5}$ cm/sec. During the stage of formation of the TC structure, the condition $\Delta t_s > \Delta t_{\text{nuc}}$ satisfied if $T_m \gtrsim 3$ keV.

Allowance for the hydrodynamic motion towards the centers can compensate for the losses to olume radiation in an optically transparent plasma at $T<4$ keV.

5. The foregoing investigation shows that the ignition condition depends on the value and imension of the initial perturbation, particularly on the ratio of the dimensions of the compressed gion in DT targets and of the region of the TC localization.

Calculations similar to those of[7,8] show that for the spherical case the resonance length is rger by approximately 50%. Then the criterion $\rho\Delta r_{nuc}$ in the spherical case will have a value 0.3–0.4 g/cm^2.

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