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The prediction, observation and study of long-distant undamped thermal waves generated in pulse radiative processes

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ABSTRACT

The problems of the existence, generation, propagation and registration of long-distant undamped thermal waves formed in pulse radiative processes have been theoretically analyzed and confirmed experimentally. These waves may be used for the analysis of short-time processes of interaction of particles or electromagnetic fields with different targets. Such undamped waves can only exist in environments with a finite (nonzero) time of local thermal relaxation and their frequencies are determined by this time. The results of successful experiments on the generation and registration of undamped thermal waves at a large distance (up to 2 m) are also presented.

1. Introduction

The problem of precise registration of interaction of particles or electromagnetic fields with different targets is very important for high-energy physics. Typically, secondary X-rays or secondary particles are used for such registration. This method requires special fast detectors with very high time resolution. Thermal effects in this interaction are considered as insignificant because traditionally it is assumed that heat waves, caused by transient radiative processes, are quickly damped and cannot be the carrier of reliable information. This conclusion is related to the traditional method of describing thermal processes and their wave equations.

Traditionally, classical Fourier's hypothesis has been used for heat conduction problems. The Fourier's hypothesis states that heat flux is proportional to the absolute value of the temperature gradient and it has the opposite direction. In a 50th of last century the first attempt to analyze non-stationary heat transfer processes was made by Cattaneo and Vernotte, that leads to a hyperbolic equation for temperature fields [1,2]. Hyperbolic and non-linear parabolic heat transfer models were studied during the second half of the twentieth century and a number of new heat transfer regimes were found, including traveling wave, blow-up regimes, and others [3]. The hypothesis of finite velocity of thermal signal propagation became especially popular in last two decades. Also, such non-stationary solutions as temperature waves started to attract the attention of researchers especially for application in scanning thermo-wave microscopy (STWM), that is a method of investigating the layers below the surface to determine heat conductivity [4–6].

Unfortunately, all these methods and models of thermal processes, which are successfully used for solving problems of modern thermodynamics, were not used for the analysis and efficient processing of the experimental data, which are related to an interaction of accelerated particles with targets. It is well known that in such interactions, local heat generation takes place. Such problems include operational analysis and measurement of the duration and structure of short bursts (bunches) of accelerated particles. Another very important problem relates to the search for methods of rapid heat removal from the interaction area.

We examined in details the problem [7–11] and came to new results, which were later confirmed in specially conducted experiments. The new methods discussed below show that more correct and adequate use of the thermal effects can be used for such tasks.

2. The wave equation for short-term or high-frequency thermal processes in material media with finite time of thermal relaxation

Let's consider a simple model of the interaction of pulsed radiation with targets when such interaction leads (among other effects of radiation) to heat release. Space–time dynamics of thermal processes $T(\vec{r},t)$ is usually analyzed in the terms of parabolic equation of thermal diffusivity:

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$$\rho c_v \frac{\partial T(\vec{r},t)}{\partial t} = div[\lambda \cdot grad(T(\vec{r},t))] \quad (1)$$

This fundamental equation follows from classical Fourier law for heat flux $\vec{q}(\vec{r},t)$

$$\vec{q}(\vec{r},t) = -\lambda \cdot grad(T(\vec{r},t)) \quad (2)$$

in a medium with thermal-conductivity coefficient λ and from the equation of continuity

$$\rho c_v \frac{\partial T(\vec{r},t)}{\partial t} = -div\vec{q}(\vec{r},t) \quad (3)$$

which follows from the energy conservation law in media with mass density ρ and heat capacity c_v. It is important to note that these fundamental Eqs. (1)(3) are based on the principle of local thermodynamic equilibrium. In the result any nonequilibrium system with temperature gradient $grad(T(\vec{r},t))$, local concentration of particles and other nonequilibrium characteristics is described by the implicit introduction of the local equilibrium states of small subsystems. Such approximations are applicable only to slow processes, when the subsystem relaxation time τ to an equilibrium state is much less than the characteristic time of the process under consideration. Typical values of τ for different material environments are given below. It is reasonable to note that a decrease in the size of the selected subsystem does not alter this situation because formation of equilibrium is determined by the interaction efficiency and not by the subsystem size.

In the case of a 1D homogeneous material environment with thermal-diffusivity coefficient $G = \lambda/\rho c_v$ the solution to the "standard" equation of thermal diffusivity

$$\frac{\partial T(x,t)}{\partial t} = G\frac{\partial^2 T(x,t)}{\partial x^2} \quad (4)$$

is the superposition of rapidly damped counter-propagating temperature waves

$$T(\omega,x,t) = A_\omega e^{i(\omega t - kx)} + B_\omega e^{i(\omega t + kx)} \equiv A_\omega e^{-\kappa x} e^{i(\omega t - \kappa x)} + B_\omega e^{\kappa x} e^{i(\omega t + \kappa x)}, \quad k = \kappa(1-i), \quad \kappa = \sqrt{\omega/2G} \quad (5)$$

It can be seen from (5) that the damping coefficient $\delta \equiv \kappa$ of both "ordinary" counter-propagating temperature waves is equal to the real part of the wave number, i.e., $k = \kappa$. As the result, these waves are attenuated at a distance comparable with the frequency-dependent wavelength, which depends on the thermodynamic parameters of a medium.

From (4) follows the expressions for phase and group velocities of thermal waves

$$v_p = \omega/\mathrm{Re}k = \pm\sqrt{2G\omega}, \quad v_g = \mathrm{Re}\{dk(\omega)/d\omega\}^{-1} = \pm\sqrt{8G\omega} \quad (6)$$

It is obvious that such strongly damped waves are poor carriers of information about radiative processes over long distances.In [7–9] we have predicted the existence of weakly damped (and under certain conditions even undamped) high frequency temperature waves, which can propagate without dissipation through material media with finite time τ of local thermal relaxation to the thermodynamic equilibrium state. The thermal-relaxation processes occur without the use of the hypothesis of instantaneous thermal relaxation and they can be properly described by the means of the modified continuity equation

$$\rho c_v \frac{\partial T(\vec{r},t+\tau)}{\partial t} = -div\vec{q}(\vec{r},t) \quad (7)$$

which corresponds to the integral relationship

$$\frac{\partial}{\partial t}\int_V W_T(\vec{r},t+\tau)dV = -\int_S \vec{q}(\vec{r},t)\vec{n}dS \quad (8)$$

Here $W_T(\vec{r},t+\tau) = \rho c_v T(\vec{r},t+\tau)$ is the volume heat-energy density and $\vec{n}$ is the vector of the external normal to the surrounding selected small-size volume V surface.

The substitution of (2) into (7) provides a time-delay equation of thermal conductivity. In the case of 1D medium, we have the following modified equation of thermal diffusivity

$$\frac{\partial T(x,t+\tau)}{\partial t} = G\frac{\partial^2 T(x,t)}{\partial x^2} \quad (9)$$

which differs from the "standard" Eq. (4) by the presence of the delay time τ (local relaxation time).

3. The reasons of existence and the mechanisms of excitation of undamped thermal waves

The solution of Eq. (9) is the superposition of counter-propagating temperature waves

$$T(\omega,x,t) = A_\omega \exp\left(-\kappa\frac{\cos\omega\tau}{\sqrt{1+\sin\omega\tau}}x\right)\exp\{i(\omega t - \kappa\sqrt{1+\sin\omega\tau}x)\} + B_\omega \exp\left(\kappa\frac{\cos\omega\tau}{\sqrt{1+\sin\omega\tau}}x\right)\exp\{i(\omega t + \kappa\sqrt{1+\sin\omega\tau}x)\}, \quad \cos\omega\tau \geqslant 0, \quad (10)$$

which is fundamentally different from "standard" solution (5) of simplified Eq. (4). For this case, we have the modified expressions for the damping coefficient δ and phase velocity

$$\delta = \kappa\frac{\cos\omega\tau}{\sqrt{1+\sin\omega\tau}} = \sqrt{\omega/2G}\frac{\cos\omega\tau}{\sqrt{1+\sin\omega\tau}} \quad (11)$$

$$v_p = \pm\sqrt{\frac{2G\omega}{1+\sin\omega\tau}} = \pm\frac{\sqrt{2G\omega}}{|\cos(\omega\tau/2)+\sin(\omega\tau/2)|} \quad (12)$$

At $\tau = 0$ solutions (5) and (10) coincide, but at $\tau \neq 0$ these results are fundamentally different.

If $\cos\omega\tau < 0$ in (10) then temperature waves with frequencies corresponding to this condition cannot be excited because their existence contradicts the causality principle, i.e., the wave amplitude increases in the propagation direction.

Waves with frequencies

$$\omega_n = (n+1/2)\pi/\tau, \quad n = 0,1,2,\ldots \quad (13)$$

which satisfy the condition $\cos\omega_n\tau = 0$, correspond to damping coefficient $\delta = 0$. In this case the general solution (10) is the superposition of forward and backward undamped temperature waves.

$$T(\omega_n,x,t) = A_{\omega_n}\exp\{i(\omega_n t - \kappa\sqrt{1+\sin\omega_n\tau}x)\} + B_{\omega_n} \times \exp\{i(\omega_n t + \kappa\sqrt{1+\sin\omega_n\tau}x)\} \quad (14)$$

The physical cause of undamped waves is related to the optimal phase relations, which determine the balance between the arrival and removal of energy in a given place and can be obtained from the dispersion equation $i\omega e^{i\omega\tau} = -k^2G$ [7–9] which follows from Eq. (9). Such a relation can exist at selected frequencies only in the absence of instantaneous, irreversible phase relaxation (at $\tau \neq 0$). Such a situation is similar to processes that take place in the quantum mechanics and the theory of oscillations (e.g. photon and phonon echo or propagation of undamped solitons in different material media).

Undamped temperature waves can be excited via at least two methods, in which the surface or volume of the medium under study is exposed to:

a) periodic thermal actions (periodic heating) with frequencies (13),
b) short heat pulses with a duration of $\Delta t < \tau$.