Generation of super-thermal hadron - anti - hadron pairs using extreme light intensities

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The big progress of high energy/intensity laser systems during the last years allowed for approaching new regimes of laser-matter interaction. In particular, by interaction of ultra-intense laser beams with plasma, electron-positron pairs can be generated via a relativistic phenomenon, which can be described by a non-Fourier heat equation. We conducted a brief analysis based upon Kozlowski-Kozlowska model in order to evaluate the laser parameters necessary to generate proton-anti-proton pairs.

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1. Introduction

The present day lasers generate intensities which easily comply with the relation: $I \cdot \lambda_\mu^2 > 10^{19}$, where I is the intensity in W/cm^2 and λ_μ is the wavelength in microns.

In consequence, it has been developed a wide range of mathematical models for high laser intensity -solid interactions [1-4].

It has been proved that at such intensities a large number of relativistic electrons with the energy given by equation (1) are produced (for full discussions see reference [5]).

$$E = \left[\sqrt{1 + \frac{I \cdot \lambda_\mu^2}{1.4 \cdot 10^{18}}} - 1 \right] \cdot m_e \cdot c^2 \qquad (1)$$

Here m_e is the electron rest mass and c is the light speed. If $I \cdot \lambda_\mu^2 >> 1.2 \cdot 10^{19} W / cm^2 \cdot \mu m^2$, we have: $E > 2 \cdot m_e \cdot c^2$.

It is considered that the positrons arise via a two-steps process in which laser photons are backscattered to GeV energies by the electron beam followed by a collision between the high energy photon and laser photons to generate electron-positron pairs.

The creation of an electron-positron pair is a relativistic process once because we have mass-energy conversion and twice because we have relativistic energies.

2. Theoretical Models

2.1 Model of laser-solid interaction

We write the heat source:

$$A(x,t) = \begin{cases} \beta \cdot \alpha_S \cdot I_0 \cdot Exp\ (-\alpha_s \cdot x), & 0 \le \mathrm{t} \le \tau \\ 0, \ \mathrm{t} < 0 \text{ and } \mathrm{t} > \tau \end{cases} \qquad (2)$$

Here β is the absorptivity of the target, τ is the pulse duration and α_S is the absorption coefficient of laser radiation in solid.

If we define τ_0 as the relaxation time (i.e. the time necessary to target to reach a new equilibrium state), we write the non-Fourier equation [1]:

$$q + \tau_0 \frac{\partial q}{\partial t} = -k \nabla T \qquad (3)$$

where q is the heat flux and k the thermal conductivity.

After some algebraic manipulations we get the relation [2]:

$$\begin{aligned} \overline{T}(x, p) = {} & A(p) Exp\left(x \sqrt{\tfrac{1}{\gamma}} (\tau_0 p^2 + p) \right) \\ & + B(p) Exp\left(- x \sqrt{\tfrac{1}{\gamma}} (\tau_0 p^2 + p) \right) \\ & - \frac{\beta I_0 (1 + \tau_0)}{\gamma \cdot p \cdot c (\alpha_s^2 - 1/\alpha(\tau_0 p^2 + p))} Exp\ (-\alpha_s \cdot x) \end{aligned} \qquad (4)$$

where:

$$B(p) = \frac{\beta I_0(1+\tau_0)}{k}\frac{1}{\sqrt{(\tau_0 p^2 + p)/\gamma}} + \frac{\beta I_0 \alpha_s(1+\tau_0)}{\gamma\rho c}\frac{1}{\sqrt{(\tau_0 p^2 + p)/\gamma}} \times \frac{1}{(\alpha_s^2 - (\tau_0 p^2 + p)/\gamma)}. \quad (5)$$

Using the reverse Laplace transform we obtain the following equation for temperature:

$$T(x,t) = \frac{\beta \cdot I_0(1+\tau_0)}{k}\sqrt{\gamma/\tau_0}\int_{x\sqrt{\tau_0/\gamma}}^{t} J_0\left(\frac{1}{2\tau_0}\sqrt{t'^2 - \tau_0 x^2/\gamma}\right)Exp(-t'/2\tau_0)dt'$$
$$+\frac{2\beta I_0\alpha_s\gamma(1+\tau_0)}{k\sqrt{1+4\gamma\alpha_s^2}}Exp(-\alpha_s x)\int_{x\sqrt{\tau_0/\gamma}}^{t} Exp(-(t-t')/2\tau_0)Sinh\sqrt{\frac{1+4\alpha_s^2\tau_0}{4\tau_0^2}(t-t')}$$
$$\times J_0\left(\frac{1}{2\tau_0}\sqrt{t'^2 - \tau_0 x^2/\gamma}\right)Exp(-t'/2\tau_0)dt' \quad (6)$$
$$+\frac{2\beta I_0\alpha_s\gamma(1+\tau_0)}{k\sqrt{1+4\gamma \cdot b^2}}Exp(-\alpha_s x)\int_0^t Exp(-t'/2\tau_0)Sinh\sqrt{\frac{1+4\gamma\alpha_s^2\tau_0}{4\tau_0^2}}t'dt'$$

where $J_0(t)$ is the zero rank Bessel function and γ is the thermal diffusivity.

2.2. Model of laser-plasma interaction: a semi-classical approach

First, we make some changes of variables in eq. (6). We thus replace α_s with α_p, the absorption coefficient of laser radiation in plasma.

α_p is further expressed as:

$$\alpha_p = 3.69\times 10^8 (Z^3 n_i^2 / T^{0.5}\nu^3)[1-\exp(-h\nu/kT)] \quad (7)$$

Here, Z, n_i and T are the average charge, ion density and temperature of plasma while $h, k,$ and ν are the Planck constant, Boltzmann constant and frequency of the laser radiation [3].

Because $\alpha_p >> 1$, we have:

$$\frac{2\beta I_0\alpha_p\gamma(1+\tau_0)}{k\sqrt{1+4\gamma\alpha_p^2}}Exp(-\alpha_p x)\int_{x\sqrt{\tau_0/\gamma}}^{t} Exp(-(t-t')/2\tau_0)Sinh\sqrt{\frac{1+4\alpha_p^2\tau_0}{4\tau_0^2}(t-t')}$$
$$\times J_0\left(\frac{1}{2\tau_0}\sqrt{t'^2 - \tau_0 x^2/\gamma}\right)Exp(-t'/2\tau_0)dt' \to 0 \quad (8)$$

Because $\alpha_s >> 1$, we have:

$$\frac{2\beta I_0\alpha_s\gamma(1+\tau_0)}{k\sqrt{1+4\gamma \cdot b^2}}Exp(-\alpha_s x)\int_0^t Exp(-t'/2\tau_0)Sinh\sqrt{\frac{1+4\gamma\alpha_s^2\tau_0}{4\tau_0^2}}t'dt' \to 0 \quad (9)$$

It results that:

$$T(x,t) = \frac{\beta \cdot I_0(1+\tau_0)}{k}\sqrt{\gamma/\tau_0}\int_{x\sqrt{\tau_0/\gamma}}^{t} J_0\left(\frac{1}{2\tau_0}\sqrt{t'^2 - \tau_0 x^2/\gamma}\right)Exp(-t'/2\tau_0)dt' \quad (10)$$

In the general case, of a laser beam consisting of superposition of decoupled transverse modes (m, n), one has:

$$T(x,t) = \sum_m \sum_n \frac{\beta \cdot I_{0,mn}(1+\tau_0)}{k} \sqrt{\gamma/\tau_0} \int_{x\sqrt{\tau_{0/\gamma}}}^{t} J_0\left(\frac{1}{2\tau_0}\sqrt{t'^2 - \tau_0 x^2/\gamma}\right) Exp(-t'/2\tau_0)dt' \qquad (11)$$

and

$$I_{0,mn}(x,y) = I_{0mn}\left[H_m\left(\frac{\sqrt{2}x}{w}\right)H_n\left(\frac{\sqrt{2}y}{w}\right)\times \exp\left[-\left(\frac{x^2+y^2}{w^2}\right)\right]\right]^2 \qquad (12)$$

We use now the following equation introduced by Kozlowski and Kozlowska [4]:

$\tau_0 \rightarrow \frac{(h/2\pi)}{m_e\alpha^2c^2}$, where α is the electromagnetic fine structure constant.

The temperature in MeV (the quanta of thermal energy for electrons is about 9 eV), versus time is presented in Fig. 1.

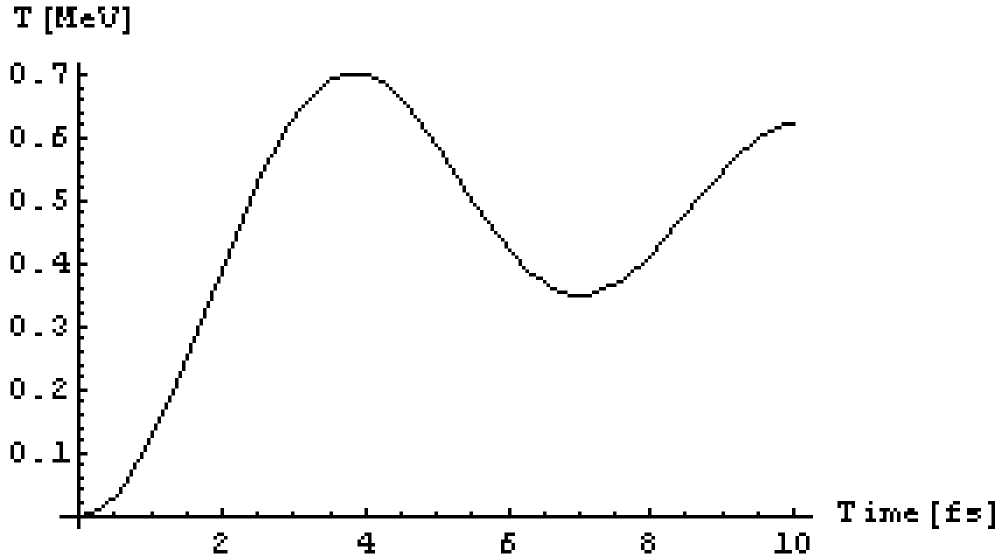

Fig. 1. Temperature versus time in the laser beam-plasma interaction.

The relaxation time is given by:

$$\tau^e = \frac{h}{m_e \cdot v_h^2} \qquad (13)$$

where v_h is the thermal pulse velocity.

We took for calculations: $v_h = 10^3 nm/ps$, the relaxation time 4 fs and the pulse duration equal with the relaxation time. We then obtained that around 4 fs a very strong increase of temperature is induced equivalent with an energy release larger than 0.511 MeV. We are therefore in the situation to generate electron-positron pairs.

We next correlated the spatial distribution of the incident laser intensity, heat transfer equation and the energy for generating particle-antiparticle pairs. We identified there main situations:

1) The heat transfer coefficient is very large ($H \rightarrow \infty$). This situation can be ensured with special cooling devices, such as a circuit with cold water surrounding the laser heated sample. In this case we do not have a strong increase in temperature and therefore we will not have production of particle-antiparticle pairs.

2) If we have a reasonable heat transfer coefficient of about $10^{-6} Wmm^{-2}K$, the temperature profile in sample is similar to the spatial distribution of the incident laser intensity. Also, the temperature gradient on surface is at least twice larger than in sample bulk. Then we will have a large number of particle-antiparticle pairs generation both on surface and in bulk. For example, in case of TEM_{01} mode we have two peaks of laser intensity in the sample bulk. We will have more particle-antiparticle pairs around the two peaks were the kinetic energy of the produced particles will be higher.

3) The sample is placed in vacuum and so $H \rightarrow 0$. In this situation the temperature gradient is linearly increasing with respect to time and is spatially uniform. We accordingly have a very large energy release, because the lost energy keeps very small, corresponding to the low heat transfer coefficient. In this situation we have particle-antiparticle pairs produced mainly at the sample surface.

3. Results: hadron anti-hadron pairs generation

Based upon the described models we calculated the laser energy necessary for the generation of hadron – anti – hadron pairs. If we denote by m_h the hadrons rest mass, we have directly from eq. (1):

$$E = \left[\sqrt{1 + \frac{I \cdot \lambda_\mu^2}{1.4 \cdot 10^{18}}} - 1 \right] \cdot m_e \cdot c^2 > 2 \cdot m_h \cdot c^2 \tag{14}$$

Consequently:

$$E = \left[\sqrt{1 + \frac{I \cdot \lambda_\mu^2}{1.4 \cdot 10^{18}}} \right] > \frac{2 \cdot m_h + m_e}{m_e} \tag{15}$$

We may write $(m_h >> m_e)$ and

$$E = \left[\sqrt{1 + \frac{I \cdot \lambda_\mu^2}{1.4 \cdot 10^{18}}} \right] \geq \frac{2 \cdot m_h}{m_e} \tag{16}$$

Accordingly we get:

$$I \cdot \lambda_\mu^2 >> \left(\left[\frac{2 \cdot m_h}{m_e} \right]^2 - 1 \right) \cdot 1.4 \cdot 10^{18} W \mu m^2 / cm^2 \approx \left[\frac{m_h}{m_e} \right]^2 \cdot 5.6 \cdot 10^{18} W / cm^2 \cdot \mu m^2 \tag{17}$$

4. Conclusions

The main conclusions of this study can be summarized as follows.

An exact analytical solution was inferred to describe the laser-solid interaction, using the Laplace transform method.

We started from a previous solution describing the laser-plasma interaction and made modifications in the final formula.

We expressed the temperature in MeV. As know, according to Kozlowski - Kozlowska theory, the heat can be quantified in heatons, which are express in eV. We observed that the energy was high enough to produce electron-positron pairs.

We considered our results an useful tool for primary evaluations. It should be regarded as a semi-classical approach, which can be further developed [6-10], to obtain quantum heat equations.

The heat transfer coefficient plays an essential role in the heat transfer modeling.

After some elementary algebra we get the threshold: $I \cdot \lambda_\mu^2 >> 2.24 \cdot 10^{25} W / cm^2 \cdot \mu m^2$ for obtaining proton – anti proton pairs, which until 2020 should be reached by ELI facility at Bucharest. Of course, if the rest mass of the hadron-anti-hadron pairs increases, the quantity $I \cdot \lambda_\mu^2$ should also increase drastically.

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