Interaction of nonthermal muon beam with electron-positron-photon plasma: A thermal field theory approach

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Interaction of nonthermal muon beam with electron-positron-photon plasma: A thermal field theory approach

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Interaction of a muon beam with hot dense QED plasma is investigated. Plasma system contains electrons and positrons with Fermi-Dirac distribution and Bose-Einstein distributed photons while the beam particles have nonthermal distribution. The energy loss of the beam particles during the interaction with plasma is calculated to complete leading order of interaction in terms of the QED coupling constant using thermal field theory approach. The screening effects of the plasma are computed consistently using resummation of perturbation theory with hard thermal loop approximation according to the Braaten-Pisarski method. Time evolution of the plasma characteristics and also plasma identifications during the interaction are investigated. Effects of the nonthermal parameter of the beam distribution on the energy exchange and the evolution of plasma-beam system are also explained.
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I. INTRODUCTION

The classical kinetic theory is one of the most powerful methods which are used to describe the behavior of plasmas. The plasma properties can be obtained with using this theory by considering the resummation on individual characteristics of particles.[1] The basic assumptions in the simple kinetic theory are such that the quantum mechanical and relativistic effects are negligible, i.e., particles are considered as classical objects and also thermal de Broglie wavelength is much larger than the distance between the particles. At high temperature and/or high pressure situations, the quantum behavior and relativistic effects in plasmas become dominant. In this case, the classical kinetic theory fails to describe the properties of such plasmas correctly and therefore one should use more advanced theories that consider particles as quantum mechanical objects and contain relativistic effects.[2,3] Quantum field theories at finite temperature are essential theories which can be used in these situations. The thermal field theory is constructed from a combination of quantum field theory (relativistic quantum mechanics) and statistical physics. It is an appropriate instrument for investigating the collective behavior of plasmas.[4] Field theory is written for systems in equilibrium states at the zero temperature. By substituting the vacuum expectation values with quantum statistic expectation values, field theory for finite temperature ($T > 0$) can be obtained.[4,5] Thus, by considering the temperature as imaginary time, the partition function can be expressed as a path integral where integrating to be carried out over closed time paths with periodicity $0 < \tau < T$. This formulation is called thermal field theory or field theory in finite temperature. Each particle of plasma interacts with other particles through physical forces; all of these possible interactions can be taken into account by employing a thermal field theory. The ultimate effect of these interactions can be expressed in the form of quasi-particles in the plasma. In some cases, the quasi-particle properties are defined as ordinary particle properties that slightly modified by their interactions with medium.[4] The thermal field theory can be applied for describing the behavior of ultrarelativistic plasmas. There are some evidences about the presence of QED and QCD plasmas in the nature while the quantum and relativistic effects are dominant in these plasmas.[6,7] At extremely high temperatures and/or densities which have been occurred in relativistic heavy ion collisions, in the core of neutron stars and in the early universe, it is expected to have plasmas that consist of quarks and gluons (QGP) which are described by quantum chromodynamics theory.[4] Also in strong electromagnetic fields and high temperatures which are observed in supernovae, neutron stars, accretion disks around black holes and in the interaction of high-intensity lasers, the Electron-Positron Plasma (EPP) are created while the quantum electrodynamics theory can be used to describe it.[8] In such issues, collective behavior of plasmas can be investigated by resummation of individual characteristics of particles using the field theory in a finite temperature. An important quantity which has been emphasized to calculate with thermal field theory is the energy loss for a heavy fermion while passing through QED or QCD plasmas.[9–20] Jet quenching, drag force, damping rate of particles in the plasma etc., will be determined directly in terms of the energy loss.[21] Furthermore, since the calculated energy loss is proportional to the heavy fermion mass, in quark-gluon plasma, it is used as an important tool to identify particles and give more information about the properties of QGP.[9,15,16] The first perturbative estimation of energy loss in a QGP has been made by Bjorken for light quarks and leptons.[22] Gluon exchange diagrams give rise to logarithmically infrared divergent integrals over the momentum transfer of the gluon in the tree-level calculation. Thoma and Gyulassy have calculated the energy loss for a heavy quark by using plasma-physics techniques.[19] Although they have correctly included the plasma effects screening the infrared divergences due to the long-range interactions, their calculations have not treated the hard momentum transfer contribution correctly. Thus, more advanced resummation methods are required for calculation of energy loss. In this regard, there are several mathematical methods including thermal field theory which is a powerful method. However in the platform of thermal field theory, the calculation of some quantities such as damping rate and energy loss of particles in plasmas cannot be obtained by calculating the Feynman diagrams only in tree level and divergences appear in the calculations. Furthermore, the results depend on the selected gauge. A successful thermal field theory should be gauge invariant and be able to screen the long-range interactions in the plasma. Braaten and Pisarski have resolved the problem of "gauge-dependent one-loop calculations of the gluon damping rate" in the thermal field theory approach by showing that thermal corrections from higher-loop diagrams contribute to the damping rate at leading order in coupling (g_s) (Ref. 23) and should be resummed. They developed a method for carrying out the resummation, in complete leading order of calculations, by introducing a resummed perturbation expansion in which the screening effects are included in a manner that the typical divergences have been improved and also the final answer is gauge independent.[24] The resummation method is based on a distinction between "hard" momenta of order T and "soft" momenta of order g_sT. If tree amplitude has soft external momenta of order g_sT, the one-loop thermal corrections proportional to T^2 contribute at the same order, in g_s, as the tree amplitude. These corrections are called "Hard Thermal Loop" (HTL) corrections, because they arise from integration regions where the loop momentum is hard. The resummation of the geometric series of HTL corrections to a propagator results an effective propagator for soft particles. In this method, effective propagators and tree level propagators are used for soft and hard particles respectively. Moreover if all connected lines to a vertex are soft, then it should be replaced by an effective vertex which includes hard thermal loop corrections.[5,25] A new method for computing the effects of screening in a hot gauge theory has been developed by Braaten and Yuan.[26] By using the Braaten and Pisarski method, they introduced an arbitrary scale q^* to separate the hard $q \gg q^*$ and soft $q \ll q^*$ regions, where q is momentum transfer. The tree level propagators are used for hard particles and effective propagators which are obtained by resummation on the HTL corrections from higher loop diagrams, are used for soft particles. The dependence on the arbitrary scale q^* cancels upon adding the hard and soft contributions to get the complete result to leading order in g_s. Based on Braaten and Yuan method, Braaten and Thoma have computed collisional energy loss for a heavy fermion propagating through a hot EPP to leading order in the QED coupling constant. They have applied perturbative thermal field theory where the required resummation methods to compute the effects of screening have been developed by imaginary-time formalism.[4] Peigné and Peshier have repeated Braaten *et al*. calculation by entering some corrections in the kinematic regions and adding more interactions which have been neglected before.[10] The EPP has been used as a toy model to calculate the collisional energy loss in Refs. 9 and 10 and in the further articles,[11,12] authors repeated this type of calculations in QGP. Since the EPP exists in the nature, the mechanism of energy transfer in this system is important by itself. In the present paper, the Braaten and Thoma method is applied to compute the energy loss dE/dx for a muon beam propagating through a hot QED plasma. A plasma system consisting of photons, thermal distributed ultra-relativistic dense electrons and positrons interacting with a muon beam has been studied. For a general investigation, a muon beam with a slightly out of thermal equilibrium distribution has been considered. The paper is organized as follows. In Sec. II, based on Braaten and Thoma approximation, the collisional energy loss dE/dx of a fast heavy muon in hot QED plasma is reviewed in terms of field theoretical quantities. The additional calculations required to extend this result for a beam of heavy fermions is described in Sec. III. In Sec. IV, we present the problem of evaluating the energy loss of an ultrarelativistic nonthermal distributed muon beam crossing a thermally equilibrated hot EPP. Finally, the main results from this investigation have been given in Secs. V and VI are devoted to conclusions and remarks.

II. COLLISIONAL ENERGY LOSS OF A FAST MUON IN HOT QED PLASMA

Our first task is to express the energy loss dE/dx of a heavy fermion in terms of field-theoretic quantities. So far, the most detailed calculation of dE/dx for a heavy fermion in a QED plasma has been presented by Braaten and Thoma.[9,10] We will start with the formula of dE/dx in Ref. 9 for an EPP and state it under the following assumptions: (1) ultrarelativistic EPP, i.e., $T \gg m_e$, (2) thermal and chemical equilibrium, (3) equal electron and positron density, i.e., vanishing chemical potential, (4) infinitely extended, homogeneous, and isotropic EPP. According to these assumptions, the distribution function of electrons and positrons is given by the Fermi-Dirac distribution $n_{FD}(|\boldsymbol{p}|) = 1/(\exp(|\boldsymbol{p}|/T) + 1)$ and of photons by the Bose-Einstein distribution $n_{BE}(|\boldsymbol{p}|) = 1/(\exp(|\boldsymbol{p}|/T) - 1)$, where the approximation $|\boldsymbol{p}| = E$ can be used for ultrarelativistic particles. It should be noted that the photons are in equilibrium with electrons and positrons under the above assumptions, i.e., the system is actually an electron-positron-photon gas. There are several types of interaction between EPP constituents and muons while moving through this medium. All of these interactions can be taken into account using some corrections which appear in propagators and vertices. In imaginary time formalism, these corrections are considered as screening effects in muon self energy.[5] The muon loses its energy during the Coulomb and Compton interactions with plasma particles as well as Bremsstrahlung process. However, the radiative loss is often much larger than collisional loss, but the collisional energy loss is comparable with radiative one for heavy fermions like muon. The radiative energy loss for heavy fermions can be neglected at small distances compared to the plasma dimensions.[14] Therefore in this condition, one can consider the collisional energy loss as the dominant mechanism for energy loss. Let us start with the collisional energy loss of an ultrarelativistic muon with mass M and energy E passing through an EPP of temperature T, with $E \gg M \gg T$. The rate of energy loss per unit distance can be calculated as

$$-\frac{dE}{dx} = \frac{1}{v}\int_M^\infty d\acute{E}(E-\acute{E})\frac{d\Gamma}{d\acute{E}}(E,\acute{E}), \tag{1}$$

where the initial and final muon four-momenta are denoted by $P=(E,\boldsymbol{p})$ and $\acute{P}=(\acute{E},\acute{\boldsymbol{P}})$, respectively. v is the muon velocity and $d\Gamma/d\acute{E}$ is the differential interaction rate with respect to the final-state muon energy. The integral extends over all final values of $\acute{E} \geq M$, and not only $\acute{E} < E$, because there is a small probability that the muon will gain energy in the collision.[4] At leading order, the energy loss per unit length for a muon arises from elastic scattering off of thermal electrons and positrons (Coulomb scattering $\mu e^{\pm} \to \mu e^{\pm}$) and photons (Compton scattering $\mu\gamma \to \mu\gamma$). The interaction rate $\Gamma(E)$ can be expressed in terms of the muon self energy $\Sigma(P)$ as[9]

$$\Gamma(E) = -\frac{1}{2E}(1-n_{FD}(E))tr[(P.\gamma+M)Im\Sigma(E+i\epsilon,p)], \tag{2}$$

where $n_{FD}(E)$ is the Fermi-Dirac distribution function for muon. The rate of damping and energy loss for a high energy muon passing through EPP with $v=1$ have been calculated as[10]

$$\Gamma(v=1) = -\frac{e^2T}{2\pi}\ln\frac{1}{e} \tag{3}$$

and

$$\frac{dE}{dx}(v=1) = \frac{(e^2T)^2}{48\pi}\left[\ln\frac{2E}{e^2T}+\frac{1}{2}\ln\frac{TE}{M^2}+0.984\right]. \tag{4}$$

In applicable situations, a beam of energetic particles interacts with target. In these situations, the problem is defined for a set of particles rather than one particle. For a beam of particles with specified energy distribution, each particle has its own energy exchange with the targeted plasma. Therefore, the distribution functions of incident beam and plasma particles evolve in time. The relaxation time of sufficient dense plasma is enough small in comparison with the beam-plasma interaction time. Therefore, one can assume that the energy propagates in the plasma rapidly in such a way that the plasma immediately finds its thermal equilibrium state in different temperature.

III. THEORETICAL FORMULATION

In this section, we extend the result for the energy loss of a fast heavy charged particle in a plasma to the case of a beam of high energy particles. In equilibrium thermal field theory, bosons and fermions are distributed with Bose-Einstein and Fermi-Dirac statistics, respectively. The situation is different if we consider the beam of particles that are not distributed in thermal equilibrium. It is clear that the distribution function of these particles changes during the interaction with plasma. The distribution function evolves in time according to initial situation of beam distribution function, physics of creation, and decay rate of the beam particles and also parameters of the targeted plasma. Consider an arbitrary non-equilibrium distribution $f(E, t=0)$ for the muon beam which has a small deviation from its equilibrium function $f_{eq} = (\exp(E/T)+1)^{-1}$. At later time t, the distribution functions becomes $f(E, t)$. The equation of time evolution for the distribution function is reported as[4,27]

$$\frac{df}{dt} = -f\Gamma^{>} + (1+f)\Gamma^{<}, \tag{5}$$

where $\Gamma^{>}$ and $\Gamma^{<}$ are the decay and creation rates of muons, respectively. For small deviation from equilibrium, the solution of Eq. (5) with an arbitrary initial momentum distribution can be written as

$$f(\boldsymbol{p},t) = f_{eq} + \delta f(\boldsymbol{p},0)\exp(-\Gamma t), \tag{6}$$

where $\Gamma = \Gamma^{>} - \Gamma^{<}$ and $f_{eq} = \Gamma^{<}/(\Gamma^{>} - \Gamma^{<})$. This equation clearly shows that the distribution function of the muon beam goes toward f_{eq} for a sufficiently large time, independent of the initial conditions. We would like to calculate the energy loss of the muon beam in this condition.

IV. THE TIME EVOLUTION OF ENERGY LOSS FOR NONTHERMAL MUON BEAM IN AN EPP

Now, we present equations for numerical simulation of the muon beam interaction with plasma particles. Consider a beam of particles which its distribution function is $f(E,t) = f_{eq} + \delta f(E)$, where $\delta f(E) \ll f_{eq}$. For small time interval Δt, a muon with initial energy E will be lost some amount of energy which can be calculated from Eq. (4), where $\Delta x = v\Delta t$. This amount of energy is absorbed by the EPP particles during the interaction. Total absorbed energy by the plasma can be calculated by integrating ΔE over all muons according to their distribution function at time t, that is, calculated from Eq. (6). The above method will be a good approximation if we choose Δt very smaller than the EPP relaxation time. This means that we take the plasma in its equilibrium state during the interaction while its temperature is increased adiabatically. The muons are assumed to be nonthermally distributed and in $t=0$ their distribution function is taken as

$$f(E,0) = \frac{1+\alpha(E/T)^2}{1+3\alpha}\exp(-E/T), \tag{7}$$

where α is a parameter defining the population of nonthermal muons.[28] Our choice of nonthermal distribution of muons is prompted by its convenience rather than as precise fitting of the observations. Fig. 1 depicts the distribution function (7) with different values of α and clearly shows that the differences between the functions are small. It is seen that the population of energetic particles increases with an increase in α. Therefore, the distribution function (7) can be considered as $f(E,t) = f_{eq} + \delta f(E)$ in which $\delta f(E) \ll f_{eq}$ and takes the form,

$$\delta f(E,0) = \frac{\alpha(E/T)^2 - 3\alpha}{1+3\alpha}\exp(-E/T). \tag{8}$$

Thus, the distribution function of muon beam from Eq. (6) becomes

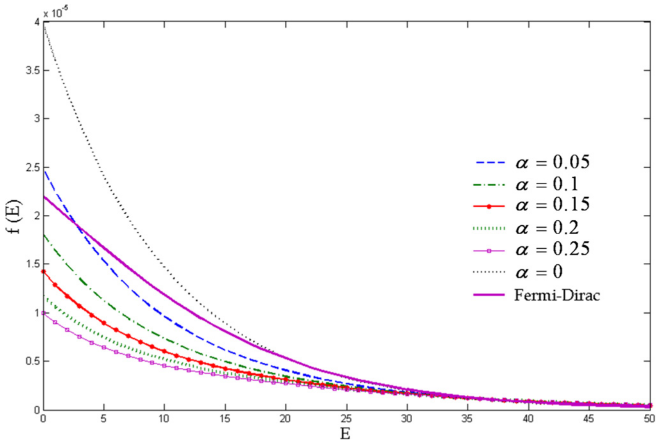

FIG. 1. Nonthermal distribution function for different values of α.

$$f(E,t) = \left[1 + \frac{\alpha(E/T)^2 - 3\alpha}{1+3\alpha}\exp(-\Gamma t)\right]\exp(-E/T). \quad (9)$$

In the following, an algorithm describing our computation method is presented. Lost energy for a muon with initial energy E during the time step Δt is calculated using Eq. (4). After that we can find a new value of the particle energy. Using the new distribution function (9) and integrating over all the particles, one can obtain the total energy loss of the beam particles during the time step, Δt. The new value of the beam temperature is therefore obtained numerically. Lost energy of the beam particle is absorbed by the plasma. We can calculate the new values of the energy and temperature for the plasma. By introducing the new values of the plasma energy, E_P, its temperature, T_P, the muon beam energy, E_B, and muon beam temperature, T_B, we can simulate the time evolution of the system during the interaction. Total energy of an EPP can be obtained as a function of its temperature as

$$E_P = \int_{-\infty}^{\infty} |\boldsymbol{p}|[2f_{FD}(|\boldsymbol{p}|) + f_{BE}(|\boldsymbol{p}|)]d^3\boldsymbol{p} = 9.003927T_P, \quad (10)$$

where the normalized Fermi-Dirac (for electrons and positrons) and Bose-Einstein distribution functions (for photons) are as follows:

$$f_{BE} = \frac{1}{8\pi T_P{}^3\zeta(3)}\frac{1}{\exp(E/T_P) - 1} \quad (11)$$

and

$$f_{FD} = \frac{1}{6\pi T_P{}^3\zeta(3)}\frac{1}{\exp(E/T_P) + 1}. \quad (12)$$

After normalization of the muon beam distribution function, we have

$$f(E,t) = \frac{\exp(-E/T_B)}{8\pi T_B{}^3}\frac{1/\alpha + 3 - (3 - (E/T_B)^2)\exp(-\Gamma t)}{1/\alpha + 3 + 9\exp(-\Gamma t)}. \quad (13)$$

Computation of the total energy of the beam and transferred energy to the plasma system yield, in respective order,

$$E_B = \int_{-\infty}^{\infty} |\boldsymbol{p}|f(|\boldsymbol{p}|,t)d^3\boldsymbol{p} = \frac{3T_B[1+3\alpha+17\alpha\exp(-\Gamma t)]}{1+3\alpha+9\alpha\exp(-\Gamma t)} \quad (14)$$

$$\left\langle\frac{dE}{dx}\right\rangle = \int_{-\infty}^{\infty}\frac{dE}{dx}f(|\boldsymbol{p}|,t)d^3\boldsymbol{p} = \frac{(e^2T_P)^2}{12}\left[\frac{3}{2}\ln(T_B) - \ln\left(\frac{e^2M\sqrt{T_P}}{2}\right) + \frac{7}{2} - \frac{1/\alpha + 3}{1/\alpha + 3 + 9\exp(-\Gamma t)}\right] \quad (15)$$

$$\langle\Delta E\rangle = \langle\Delta x\rangle\left\langle\frac{dE}{dx}\right\rangle, \quad (16)$$

where ΔE is the injected energy to the plasma system. The time step Δt should be taken sufficiently small in such a way that the transferred energy (and therefore the change in the distribution function) becomes small. After the time step Δt, it is straightforward to obtain

$$\acute{E}_P = E_P + \langle\Delta E\rangle \quad (17)$$

and

$$\acute{E}_B = E_B - \langle\Delta E\rangle, \quad (18)$$

which correspond to energy of the plasma and beam particles, respectively. As ΔE is small, one can suppose that the plasma remains in equilibrium state but with different value of temperature. The new temperature value of the plasma can be obtained using Eq. (19) and the new temperature of the beam is calculated by solving Eq. (14). Thus, the energy and the temperature of the beam and plasma can be calculated after the time step Δt. In the remainder of this work, we present our final results for evaluating the energy loss of an ultrarelativistic nonthermal distributed muon beam crossing a thermally equilibrated hot EPP.

V. NUMERICAL RESULTS AND DISCUSSIONS

We now proceed with the presentation of our numerical simulation. Our results are plotted in Figs. 2–9, with considering a nonthermal distributed muon beam interacted with a hot and dense EPP. The muon beam distribution function will change during the interaction with EPP. The beam distribution functions for several values of the parameter α at times $t=0$, $t=2000$, and $t=2500$ are presented in Figs. 2–4, respectively. These figures show that the distribution function goes toward the equilibrium situation for all values of the parameter α. It may be noted that the temperature of the muon beam and plasma change during the interaction. Fig. 5 presents the rate of energy loss as a function of time with different values of nonthermal parameter α. This figure indicates that the rate of the energy transfer from the beam to the plasma increases up to a maximum value and after that decreases to zero. The maximum energy transfer is a function of nonthermal parameter α. Fig. 5 clearly shows that the transferred energy enhances as nonthermal parameter α increases. This means that the energy loss of energetic particles is more than the low energy particles of the beam. Fig. 6 demonstrates the rate of energy transfer as a function of time for several values of the beam initial temperature.

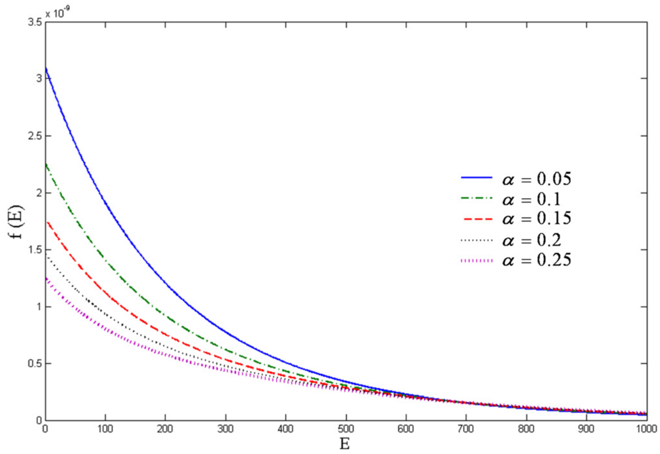

FIG. 2. Beam distribution function at $t = 0$ for different values of α with initial conditions $T_P = 10\,\mathrm{MeV}, T_B = 200\,\mathrm{MeV}$.

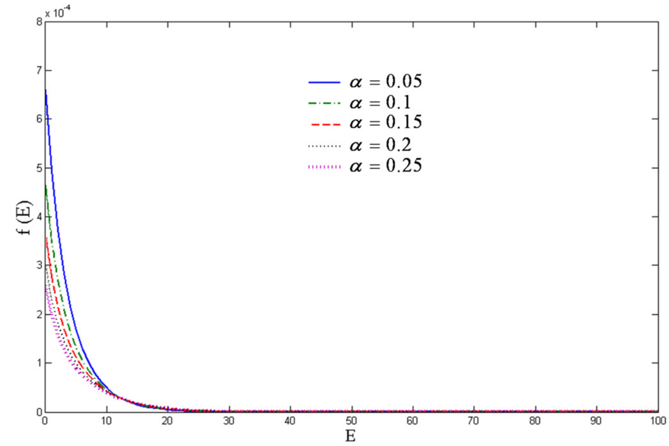

FIG. 4. Beam distribution function at $t = 2500$ for different values of α with initial conditions $T_P = 10\,\mathrm{MeV}, T_B = 200\,\mathrm{MeV}$.

The maximum value of the energy transfer rate increases nonlinearly as the initial value of T_B increases. The rate of transferred energy of beams with higher temperature has sharper changes in comparison with beams in lower initial temperatures. Sharpness of the energy transfer rate during the interaction with beam particles is one of the sources of turbulence in plasmas. Fig. 7 demonstrates time evolution of beam and plasma temperatures. This figure shows that beam temperature decreases in time while the temperature of the plasma increases. The change rate of the temperatures decreases for both the beam particle and the plasma, so they find their steady state situations. The equilibrium state is a function of initial conditions of the beam and plasma characteristics. It is also seen that the final temperature of the plasma is a function of the nonthermal parameter of the beam distribution function. Fig. 7 presents that the final temperature of the plasma increases as nonthermal parameter α increases. It is natural, because the population of energetic particles increases with α and therefore, the rate of transferred energy increases with an increasing value of nonthermal parameter. The dependence of the final temperature on α is very significant. This shows that the nonthermal effect is very important. Fig. 8 demonstrates the tine evolution of beam and plasma energies for different values α. Outcomes of the Fig. 8 are in agreement with the results of Fig. 7. The time evolution of beam and plasma temperatures for different initial T_P are shown in Fig. 9. It is clear that the energy transfer in high temperature plasmas is greater than that of low temperature plasmas. This implies that high temperature plasma finds its equilibrium state faster than plasmas with low temperature. The presented model in previous sections describes the injection of nonthermal beam of fermions into the thermalized plasma. Indeed, under a very occasional condition, the plasma response is non-resonant and the targeted plasma can be considered as a bulk during the interaction with the beam. Contribution due to the boundary surfaces of the system generally cannot be neglected in comparison with the bulk. This means that the evolution of an element of the plasma system is affected by all the other particles in the medium. Therefore, long range interactions have to be considered in the evolution of the system. Generating Langmuir modes, long-range-coupling the charged particles via electrostatic waves,[29,30] quantum Fluctuations, and radiative-resonant interactions (RRIs)[31] are the main sources of long-range interactions in the system. The beam-plasma instabilities are examples of the long-range effects. In most of the cases, the system becomes unstable by the long-range effects and the instability amplitude increases up to a maximum value and the system attains an oscillatory regime of the

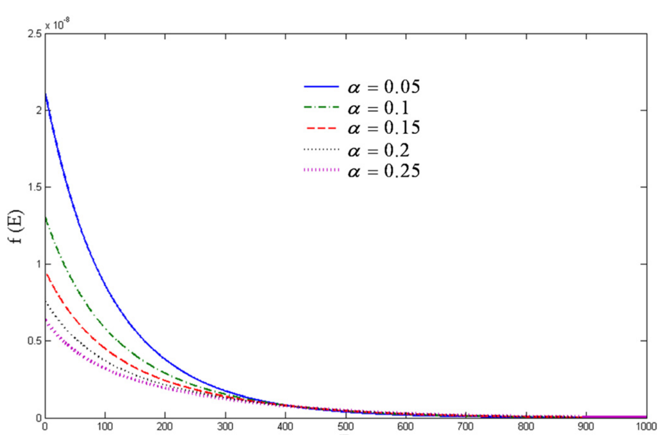

FIG. 3. Beam distribution function at $t = 2000$ for different values of α with initial conditions $T_P = 10\,\mathrm{MeV}, T_B = 200\,\mathrm{MeV}$.

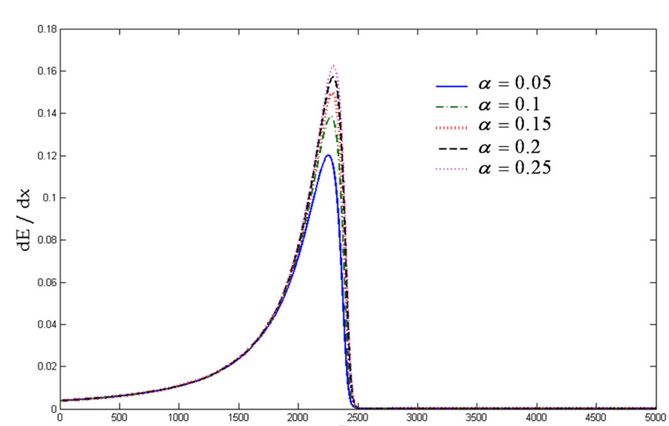

FIG. 5. Time evolution of the energy loss rate for different values of α with initial conditions $T_P = 10\,\mathrm{MeV}, T_B = 200\,\mathrm{MeV}$.

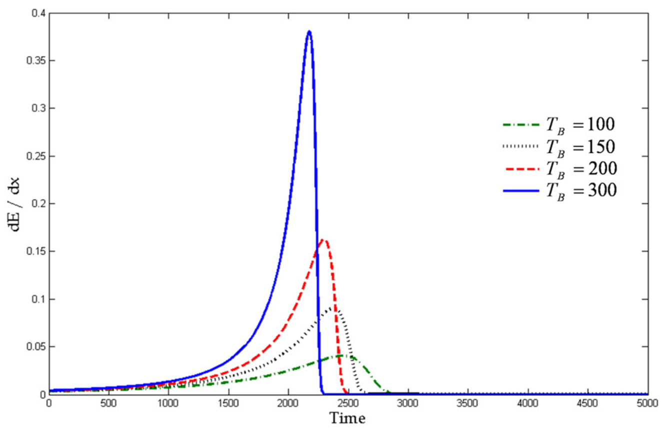

FIG. 6. Time evolution of the energy transfer rate for different values of beam temperature with initial conditions $T_P = 10\,\text{MeV}$ and $\alpha = 0.25$.

wave intensity. The wave amplitude grows until the particles of the beam are trapped by the propagated wave and then it starts oscillating because of the beam-potential interaction. Therefore, distribution functions of beam and plasma particles evolve during the beam-wave interaction. Investigations have shown that there exists a threshold value of the initial distribution for beam particles which separates the resonant and non-resonant regimes.[32] As the beam particles in our problem (muons) are very massive, the effects of beam-plasma interaction on the beam distribution function are negligible while the collective effects on the plasma are great. The Langmuir modes of electromagnetic waves and radiative-resonant interactions create more important long range effects in beam-plasma systems. It is shown that electrostatic potentials oscillate with frequencies close to the plasma frequency defined by $\omega_P = e^2n^2/\epsilon_0 m^2$, where n is the electron density of the plasma, e the electron charge, m the electron mass, and ϵ_0 the vacuum permittivity, respectively.[29] Distribution of plasma particles oscillate during the interaction with the electromagnetic field and thus the plasma components are not in thermal equilibrium. Simulations show that such oscillations slightly increase superthermal particles in the plasma components[32] Therefore, one can use modified superthermal distribution

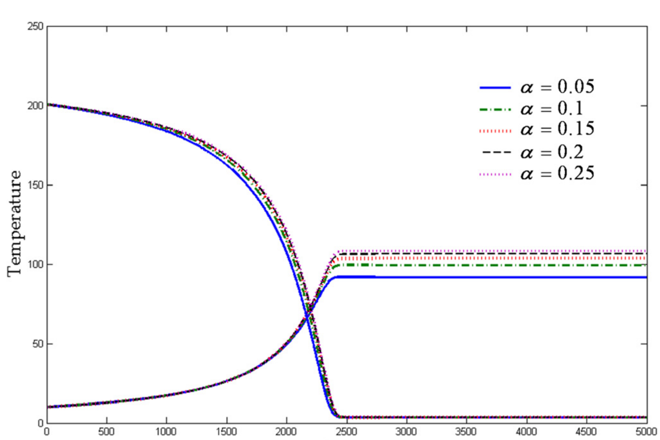

FIG. 7. The temperature of plasma and beam versus time for different α with initial conditions $T_P = 10\,\text{MeV}, T_B = 200\,\text{MeV}$.

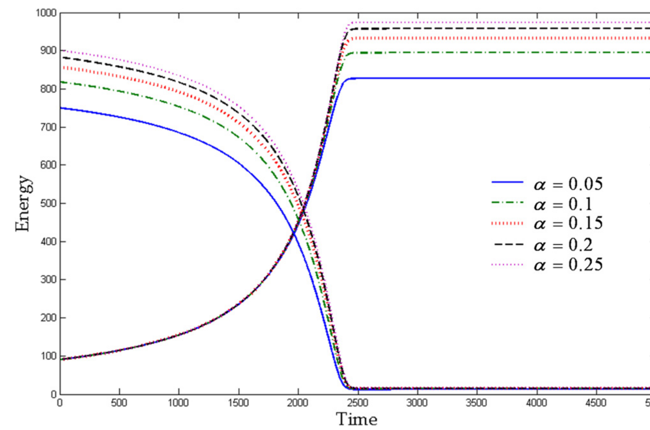

FIG. 8. The energy of plasma and beam versus time for different values of α with initial conditions $T_P = 10\,\text{MeV}, T_B = 200\,\text{MeV}$.

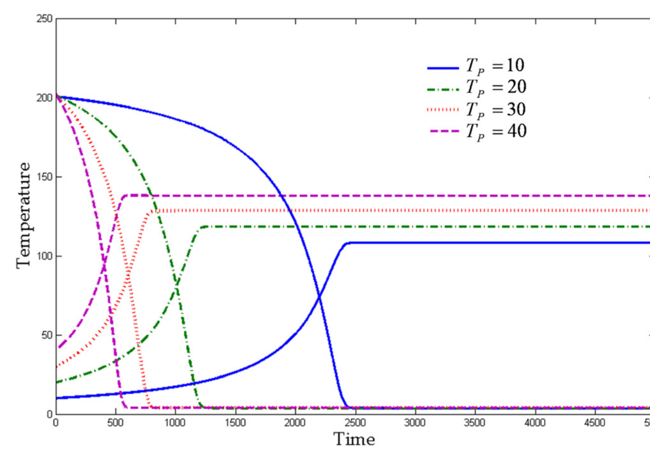

FIG. 9. Time evolution of the plasma and beam temperature with initial conditions $T_B = 200\,\text{MeV}$ and $\alpha = 0.25$.

function for charged constituents of plasma. On the other hand, the RRIs have a substantial effect on the beam-plasma interaction. It is shown that the RRIs can result in the changes in the populations of electrons and positrons by creating fast electrons with the rate[33,34]

$$\frac{dn^f_{e^-}}{dt} = \sqrt{\frac{n_{e^-}}{n_{e^+}}}\frac{W}{n_{e^-}T_{e^-}}\left(\frac{\nu_{Te^-}}{c}\right)^2\omega_{Pe^-}, \tag{19}$$

where W is the wave energy density and e^- and e^+ stands for the values corresponding to electrons and positrons, respectively. The above equation also indicates that one can use a superthermal distribution function for the electron density. Therefore, it can be concluded that using a modified superthermal distribution function for the electron and positrons may results a better answer. It may be noted that the presented simulations have been done for fast particles. The above corrections create very complicated situations according to the initial conditions which needs deeper investigations.

VI. CONCLUSIONS AND REMARKS

In this work, the interaction of an ultrarelativistic nonthermal distributed muon beam with a hot and dense electron-positron plasma is investigated. In order to construct our model, we have applied Braaten and Thoma approximation and presented the collisional energy loss for a beam of heavy fermion in a QED plasma in terms of the physical parameters of interest. The effect of various parameters such as the time evolution of beam particles distribution function, beam energy, its temperature as well as plasma temperature and its energy has been examined. Based on our numerical results, the rate of energy beam exchange increases with the increase of the initial temperature of the beam. Also simulations show that high temperature plasmas find their equilibrium situation faster than low temperature plasmas. Furthermore, the effects of nonthermal parameter on the characteristics of plasma and beam are discussed in detail. It is shown that the rate of energy exchange between the beam and plasma increases as the nonthermal parameter increases. Our numerical analysis reveals that the maximum energy transfer is a nonlinear function of nonthermal parameter α. The effects of long-range interactions due to Langmuir modes of electromagnetic waves and radiative-resonant interactions are also briefly discussed. It is shown that the distribution function of electrons approaches to a superthermal like function. As muons are massive, so the long-range effects on the beam distribution is negligible. Although this study has provided us with useful information for interaction of a nonthermal muon beam with QED plasma, investigations of different kinds of distributions and other plasma systems are the subject for further research. We think that the present investigation will be helpful in understanding the mechanism of energy transfer in ultrarelativistic EPP in finite temperature which occurs in space and laboratories. Such plasmas for example can be observed around supernova stars. In this case, high energy muon beam also can be emitted by the core of the supernova. It is noted that a supernova generally is detected by its emitted muons-neutrinos which are created together with muons.

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