On Plasma Oscillations in Strong Electric Fields

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Abstract

We describe the creation and evolution of electron-positron pairs in a strong electric field as well as the pairs annihilation into photons. The formalism is based on generalized Vlasov equations, which are numerically integrated. We recover previous results about the oscillations of the charges, discuss the electric field screening and the relaxation of the system to a thermal equilibrium configuration. The timescale of the thermalization is estimated to be $\sim 10^3 - 10^4 \frac{\hbar}{m_e c^2}$.

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Three different earth-bound experiments and one astrophysical observation have been proposed for identifying the polarization of the electronic vacuum due to a supercritical electric field ($E > E_c \equiv \frac{m_e^2 c^3}{e \hbar}$, where $m_e$ and $e$ are the electron mass and charge) postulated by Sauter-Heisenberg-Euler-Schwinger [1]:

(1) In central collisions of heavy ions near the Coulomb barrier, as first proposed in [2,3] (see also [4,5,6]). Despite some apparently encouraging results [7], such efforts have failed so far due to the small contact time of the colliding ions [8,9,10,11,12]. Typically the electromagnetic energy involved in the collisions of heavy ions with impact parameter $l_1 \sim 10^{-12}$cm is $E_1 \sim 10^{-6}$erg and the lifetime of the diatomic system is $t_1 \sim 10^{-22}$s.

(2) In collisions of an electron beam with optical laser pulses: a signal of positrons above background has been observed in collisions of a 46.6 GeV electron beam with terawatt pulses of optical laser in an experiment at

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the Final Focus Test Beam at SLAC [13]; it is not clear if this experimental result is an evidence for the vacuum polarization phenomenon. The energy of the laser pulses was $E_2 \sim 10^7$ erg, concentrated in a space-time region of spacial linear extension (focal length) $l_2 \sim 10^{-3}$ cm and temporal extension (pulse duration) $t_2 \sim 10^{-12}$ s [13].

(3) At the focus of an X-ray free electron laser (XFEL) (see [14,15,16] and references therein). Proposals for this experiment exist at the TESLA collider at DESY and at the LCLS facility at SLAC [14]. Typically the electromagnetic energy at the focus of an XFEL can be $E_3 \sim 10^6$ erg, concentrated in a space-time region of spacial linear extension (spot radius) $l_3 \sim 10^{-8}$ cm and temporal extension (coherent spike length) $t_3 \sim 10^{-13}$ s [14].

and from astrophysics

(1) around an electromagnetic black hole (EMBH) [17,18,19], giving rise to the observed phenomenon of gamma-ray bursts (GRB) [20,21,22,23]. The electromagnetic energy of an EMBH of mass $M \sim 10M_\odot$ and charge $Q \sim 0.1M/\sqrt{G}$ is $E_4 \sim 10^{54}$ erg and it is deposited in a space-time region of spacial linear extension $l_4 \sim 10^8$ cm [18,24] and temporal extension (collapse time) $t_4 \sim 10^{-2}$ s [25].

In addition to their marked quantitative difference in testing the same basic physical phenomenon, there is a very important conceptual difference among these processes: the first three occur in a transparency condition in which the created electron-positron pairs and, possibly, photons freely propagate to infinity, while the one in the EMBH occurs in an opacity condition [26]. Under the opacity condition a thermalization effect occurs and a final equipartition between the $e^+e^-$ and $\gamma$ is reached. Far from being just an academic issue, this process and its characteristic timescale is of the greatest importance in physics and astrophysics. It has been shown by a numerical simulation done in Livermore and an analytic work done in Rome [26], that, as soon as the thermalization of $e^+e^-$ and $\gamma$ created around an EMBH has been reached, the plasma self propells outwards and this process is at the very heart of the gamma-ray burst (GRB) phenomenon. A critical step was missing up to now: how to bridge the gap between the creation of pairs in the supercritical field of the EMBH and the thermalization of the system to a plasma configuration. This letter reports some progress on this topic with special attention to the timescale needed for the thermalization of the newly created $e^+e^-$ pairs in the background field. The comparison of the thermalization timescale to the one of gravitational collapse, which occurs on general relativistic timescale, is at the very ground of the comprehension of GRBs [25].

The evolution of a system of particle-antiparticle pairs created by the Schwinger process has been often described by a transport Vlasov equation (see, for ex-
ample, [27,28]). More recently it has been showed that such an equation can be derived from quantum field theory [29,30,31]. In the homogeneous case, the equations have been numerically integrated taking into account the back reaction on the external electric field [32,33,34,35]. In many papers (see [36] and references therein) a phenomenological term describing equilibrating collisions is introduced in the transport equation which is parameterized by an effective relaxation time $\tau$. In [36] one further step is taken by allowing time variability of $\tau$; the ignorance on the collision term is then parameterized by a free dimensionless constant. The introduction of a relaxation time corresponds to the assumption that the system rapidly evolves towards thermal equilibrium. In this paper we focus on the evolution of a system of $e^+e^-$ pairs, explicitly taking into account the scattering processes $e^+e^- \leftrightarrow \gamma\gamma$. Since we are mainly interested in a system in which the electric field varies on macroscopic length scale ($l \sim 10^8$ cm, above), we can limit ourselves to a homogeneous electric field. Also, we will use transport equations for electrons, positrons and photons, with collision terms, coupled to Maxwell equations. There is no free parameter here: the collision terms can be exactly computed, since the QED cross sections are known. Starting from a regime which is far from thermal equilibrium, we find that collisions do not prevent plasma oscillations in the initial phase of the evolution and analyse the issue of the timescale of the approach to a $e^+e^-\gamma$ plasma equilibrium configuration, which is the most relevant quantity in the process of gravitational collapse [25].

The motion of positrons (electrons) is the resultant of three contributions: the pair creation, the electric acceleration and the annihilation damping. The homogeneous system consisting of electric field, electrons, positrons and photons can be described by the equations

$$\partial_t f_e + eE \partial_p f_e = \mathcal{S}(E,p) - \frac{1}{(2\pi)^3} \epsilon_p^{-1} \mathcal{C}_e(t,p), \quad (1)$$
$$\partial_t f_\gamma = \frac{2}{(2\pi)^3} \epsilon_k^{-1} \mathcal{C}_\gamma(t,k), \quad (2)$$
$$\partial_t E = -j_p(E) - j_e(t), \quad (3)$$

where $f_e = f_e(t,p)$ is the distribution function in the phase-space of positrons (electrons), $f_\gamma = f_\gamma(t,k)$ is the distribution function in the phase-space of photons, $E$ is the electric field, $\epsilon_p = (p \cdot p + m_e^2)^{1/2}$ is the energy of an electron of 3-momentum $p$ ($m_e$ is the mass of the electron) and $\epsilon_k = (k \cdot k)^{1/2}$ is the energy of a photon of 3-momentum $k$. $f_e$ and $f_\gamma$ are normalized so that

$$\int \frac{d^3p}{(2\pi)^3} f_e(t,p) = n_e(t), \quad \int \frac{d^3k}{(2\pi)^3} f_\gamma(t,k) = n_\gamma(t),$$

where $n_e$ and $n_\gamma$ are number densities of positrons (electrons) and photons, respectively. The term

$$\mathcal{S}(E,p) = (2\pi)^3 \frac{dN}{dEd\omega d^3p} = -|eE| \log \left[ 1 - \exp \left( -\frac{\pi(m_e^2 + p_\parallel^2)}{|eE|} \right) \right] \delta(p_\parallel) \quad (4)$$

is the Schwinger source for pair creation (see [32,33]): $p_\parallel$ and $p_\perp$ are the components of the 3-momentum $p$ parallel and orthogonal to $E$. We assume
We also have, in Eqs. (1), (2) and (3),
\[ C_e(t, p) \simeq \int \frac{d^3p_1}{\epsilon_{k_1}} \frac{d^3k_1}{\epsilon_{k_1}} \frac{d^3p_2}{\epsilon_{k_2}} \frac{d^3k_2}{\epsilon_{k_2}} \delta^{(4)} (p + p_1 - k_1 - k_2) \times |M|^2 [f_e(p)f_e(p_1) - f_{\gamma}(k_1)f_{\gamma}(k_2)], \]
(5)
\[ C_{\gamma}(t, k) \simeq \int \frac{d^3p_1}{\epsilon_{p_1}} \frac{d^3p_2}{\epsilon_{p_2}} \frac{d^3k_1}{\epsilon_{k_1}} \delta^{(4)} (p_1 + p_2 - k_1 - k_2) \times |M|^2 [f_e(p_1)f_e(p_2) - f_{\gamma}(k)f_{\gamma}(k_1)], \]
(6)

which describe probability rates for pair creation by photons and pair annihilation into photons, \( M = M_{e^+(p_1)e^-(p_2)\rightarrow \gamma(k)\gamma(k_1)} \) being the matrix element for the process \( e^+(p_1)e^-(p_2) \rightarrow \gamma(k)\gamma(k_1) \). Note that the collisional terms (5) and (6) are either unapplicable or negligible in the case of the above three earth-bound experiments where the created pairs do not originate a dense plasma. They have been correctly neglected in previous works (see e.g. [16]). Collisional terms have also been considered in the different physical context of vacuum polarization by strong chromoelectric fields. Unlike the present QED case, where expressions for the cross sections are known exactly, in the QCD case the cross sections are yet unknown and such collisional terms are of a phenomenological type and useful uniquely near the equilibrium regime [36]. Finally \( \mathbf{j}_p(E) = 2E \mathbf{E} \int \frac{d^3p}{(2\pi)^3} \epsilon_p S(E, p) \) and \( \mathbf{j}_e(t) = 2en_e \int \frac{d^3p}{(2\pi)^3} \epsilon_p f_e(p) \) are polarization and conduction current respectively (see [28]). In Eqs. (5) and (6) we neglect, as a first approximation, Pauli blocking and Bose enhancement (see e.g. [33]). By suitably integrating (1) and (2) over the phase spaces of positrons (electrons) and photons, we find the following exact equations for mean values:
\[
\frac{d}{dt}n_e = S(E) - n_e^2 \langle \sigma_1 v' \rangle_e + n_e^2 \langle \sigma_2 v'' \rangle_{\gamma},
\]
\[
\frac{d}{dt}n_{\gamma} = 2n_e^2 \langle \sigma_1 v' \rangle_e - 2n_{\gamma}^2 \langle \sigma_2 v'' \rangle_{\gamma},
\]
\[
\frac{d}{dt}n_e \langle \epsilon_p \rangle_e = en_eE \cdot \langle v \rangle_e + \frac{1}{2} \mathbf{E} \cdot \mathbf{j}_p - n_e^2 \langle \epsilon_p \sigma_1 v' \rangle_e + n_e^2 \langle \epsilon_p \sigma_2 v'' \rangle_{\gamma},
\]
\[
\frac{d}{dt}n_{\gamma} \langle \epsilon_k \rangle_{\gamma} = 2n_e^2 \langle \epsilon_p \sigma_1 v' \rangle_e - 2n_{\gamma}^2 \langle \epsilon_k \sigma_2 v'' \rangle_{\gamma},
\]
\[
\frac{d}{dt}n_e \langle \mathbf{p} \rangle_e = en_eE - n_e^2 \langle \mathbf{p} \sigma_1 v' \rangle_e,
\]
\[
\frac{d}{dt}\mathbf{E} = -2en_e \langle \mathbf{v} \rangle_e - \mathbf{j}_p(E),
\]
(7)

where, for any function of the momenta
\[
\langle F(p_1, \ldots, p_n) \rangle_e \equiv n_e^{-n} \int \frac{d^3p_1}{(2\pi)^3} \ldots \frac{d^3p_n}{(2\pi)^3} F(p_1, \ldots, p_n) \cdot f_e(p_1) \cdot \ldots \cdot f_e(p_n),
\]
(8)
\[
\langle G(k_1, \ldots, k_l) \rangle_{\gamma} \equiv n_{\gamma}^{-l} \int \frac{d^3k_1}{(2\pi)^3} \ldots \frac{d^3k_l}{(2\pi)^3} G(k_1, \ldots, k_l) \cdot f_{\gamma}(k_1) \cdot \ldots \cdot f_{\gamma}(k_l).
\]
(9)
Furthermore \( v' \) is the relative velocity between electrons and positrons, \( v'' \) is the relative velocity between photons, \( \sigma_1 = \sigma_1(\epsilon_p^{\text{CoM}}) \) is the total cross section for the process \( e^+e^- \rightarrow \gamma\gamma \) and \( \sigma_2 = \sigma_2(\epsilon_k^{\text{CoM}}) \) is the total cross section for
the process $\gamma \gamma \to e^+e^-$ (here $\epsilon_{\text{CoM}}$ is the energy of a particle in the reference frame of the center of mass).

In order to evaluate the mean values in system (7) we need some further hypotheses on the distribution functions. Let us define $\bar{p}_\parallel$, $\bar{\epsilon}_p$ and $\bar{p}_\perp$ such that $\langle p_\parallel \rangle_e = \bar{p}_\parallel$, $\langle \epsilon_p \rangle_e = \bar{\epsilon}_p \equiv (\bar{p}_\parallel^2 + \bar{p}_\perp^2 + m^2_e)^{1/2}$. We assume

$$f_e \left( t, p \right) \propto n_e \left( t \right) \delta \left( p_\parallel - \bar{p}_\parallel \right) \delta \left( \bar{p}_\perp^2 - p_\perp^2 \right).$$

(10)

Since in the scattering $e^+e^- \to \gamma \gamma$ the coincidence of the scattering direction with the incidence direction is statistically favored, we also assume

$$f_\gamma \left( t, k \right) \propto n_\gamma \left( t \right) \delta \left( k_\perp - \bar{k}_\perp \right) \left[ \delta \left( k_\parallel - \bar{k}_\parallel \right) + \delta \left( k_\parallel + \bar{k}_\parallel \right) \right],$$

(11)

where $k_\parallel$ and $k_\perp$ have analogous meaning as $p_\parallel$ and $p_\perp$ and the terms $\delta \left( k_\parallel - \bar{k}_\parallel \right)$ and $\delta \left( k_\parallel + \bar{k}_\parallel \right)$ account for the probability of producing, respectively, forwardly scattered and backwardly scattered photons. Since the Schwinger source term (4) implies that the positrons (electrons) have initially fixed $p_\parallel$, $p_\parallel = 0$, assumption (10) ((11)) means that the distribution of $p_\parallel$ ($k_\parallel$) does not spread too much with time and, analogously, that the distribution of energies is sufficiently peaked to be describable by a $\delta$–function. The dependence on the momentum of the distribution functions has been discussed in [33,30]. Approximations (10), (11) reduce Eqs. (7) to a system of ordinary differential equations. In average, since the inertial reference frame we fix coincides with the center of mass frame for the processes $e^+e^- \leftrightarrow \gamma \gamma$, $\epsilon_{\text{CoM}} \approx \bar{\epsilon}$ for each species. Substituting (10) and (11) into (7) we find

$$\frac{d}{dt} n_e = S \left( \mathcal{E} \right) - 2n_e^2 \sigma_1 \rho_\gamma^{-1} \left| \pi_\parallel \right| + 2n_e^2 \sigma_2,$$

$$\frac{d}{dt} n_\gamma = 4n_e^2 \sigma_1 \rho_\gamma^{-1} \left| \pi_\parallel \right| - 4n_e^2 \sigma_2,$$

$$\frac{d}{dt} \rho_\gamma = e n_e \mathcal{E} \rho_\gamma^{-1} \left| \pi_\parallel \right| + \frac{1}{2} \mathcal{E} j_p - 2n_e \rho_e \sigma_1 \rho_\gamma^{-1} \left| \pi_\parallel \right| + 2n_e \rho_\gamma \sigma_2,$$

$$\frac{d}{dt} \rho_\gamma = 4n_e \rho_e \sigma_1 \rho_\gamma^{-1} \left| \pi_\parallel \right| - 4n_e \rho_\gamma \sigma_2,$$

$$\frac{d}{dt} \pi_\parallel = e n_e \mathcal{E} - 2n_e \pi_\parallel \sigma_1 \rho_\gamma^{-1} \left| \pi_\parallel \right|,$$

$$\frac{d}{dt} \mathcal{E} = -2e n_e \rho_\gamma^{-1} \left| \pi_\parallel \right| - j_p \left( \mathcal{E} \right),$$

(12)

where $\rho_e = n_e \bar{\epsilon}_p$, $\rho_\gamma = n_\gamma \bar{\epsilon}_k$, $\pi_\parallel = n_e \bar{p}_\parallel$ are the energy density of positrons (electrons), the energy density of photons and the density of “parallel momentum” of positrons (electrons), $\mathcal{E}$ is the electric field strength and $j_p$ the unique component of $j_e$ parallel to $\mathbf{E}$. $\sigma_1$ and $\sigma_2$ are evaluated at $\epsilon_{\text{CoM}} = \bar{\epsilon}$ for each species. Note that Eqs. (12) are “classical” in the sense that the only quantum information is encoded in the terms describing pair creation and scattering probabilities. Eqs. (12) are consistent with energy density conservation:

$$\frac{d}{dt} \left( \rho_e + \rho_\gamma + \frac{1}{2} \mathcal{E}^2 \right) = 0.$$
The initial conditions for Eqs. (12) are \( n_e = n_\gamma = \rho_e = \rho_\gamma = \pi_{e\parallel} = 0, \ E = \mathcal{E}_0 \). In Fig. 1 the results of the numerical integration for \( \mathcal{E}_0 = 9 \mathcal{E}_c \) is showed. The integration stops at \( t = 150 \ \tau_C \) (where \( \tau_C = \hbar/m_e c^2 \)). Each variable is represented in units of \( m_e \) and \( \lambda_C = \hbar/m_e c \). The numerical integration confirms \([32,33]\) that the system undergoes plasma oscillations: a) the electric field oscillates with decreasing amplitude rather than abruptly reaching the equilibrium value; b) electrons and positrons oscillates in the electric field direction, reaching ultrarelativistic velocities; c) the role of the \( e^+e^- \leftrightarrow \gamma\gamma \) scatterings is marginal in the early time of the evolution, the electrons are too extremely relativistic and consequently the density of photons builds up very slowly (see details in Fig. 1).

At late times the system is expected to relax to a plasma configuration of thermal equilibrium and assumptions (10) and (11) have to be generalized to take into account quantum spreading of the distribution functions. It is nevertheless interesting to look at the solutions of Eqs. (12) in this regime. In Fig. 2 we plot the numerical solution of Eqs. (12) but the integration extends here all the way up to \( t = 7000 \ \tau_C \) (the time scale of oscillations is not resolved in these plots). It is interesting that the leading term recovers the expected asymptotic behaviour: a) the electric field is screened to about the critical value: \( \mathcal{E} \simeq \mathcal{E}_c \) for \( t \sim 10^3 - 10^4 \tau_C \gg \tau_C \); b) the initial electromagnetic energy density is distributed over electron-positron pairs and photons, indicating energy equipartition; c) photons and electron-positron pairs number densities are asymptotically comparable, indicating number equipartition. At such late times a regime of thermalized electrons-positrons-photons plasma begins and the system is describable by hydrodynamic equations \([25,26]\).

We provided a very simple formalism apt to describe simultaneously the creation of electron-positron pairs by a strong electric field \( \mathcal{E} \gtrsim \mathcal{E}_c \) and the pairs annihilation into photons. As discussed in literature, we find plasma oscillations. In particular the collisions do not prevent such a feature. This is because the momentum of electrons (positrons) is very high, therefore the cross section for the process \( e^+e^- \rightarrow \gamma\gamma \) is small and the annihilation into photons is negligible in the very first phase of the evolution. As a result, the system takes some time \( t \sim 10^3 - 10^4 \tau_C \) to thermalize to a \( e^+e^-\gamma \) plasma equilibrium configuration. We finally remark that, at least in the case of electromagnetic Schwinger mechanism, the picture could be quite different from the one previously depicted in literature, where the system is assumed to thermalize in a very short time (see \([36]\) and references therein).

It is conceivable that in the race to first identify the vacuum polarization process à la Sauter-Euler-Heisenberg-Schwinger, the astrophysical observations will reach a positive result before earth-bound experiments, much like in the case of the discovery of lines in the Sun chromosphere by J. N. Lockyer in 1869, later identified with the Helium spectral lines by W. Ramsay in 1895.
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Fig. 1. Plasma oscillations. We set $\mathcal{E}_0 = 9\mathcal{E}_c$, $t < 150\tau_C$ and plot: a) electromagnetic field strength; b) electrons energy density; c) electrons number density; d) photons energy density; e) photons number density as functions of time.
Fig. 2. Plasma oscillations. We set $E_0 = 9E_c$, $t < 7000\tau_C$ and plot: a) electromagnetic field strength; b) electrons energy density; c) electrons number density; d) photons energy density; e) photons number density as functions of time - the oscillation period is not resolved in these plots. The model used should have a breakdown at a time much earlier than $7000\tau_C$ and therefore this plot contains no more than qualitative informations.