Pair Production by Ultraintense Lasers

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We consider the production of electron-positron pairs by the interaction of relativistic superthermal electrons, generated by ultraintense laser pulses, with high-Z material. We discuss the laser and target parameters required in order to optimize the pair-production rate. We explore the regime when the pairs, if sufficiently confined, can start to exponentiate in number and explore the feasibility of achieving a pair density approaching 10^{21} cm^{-3}, $\frac{1}{50}$th that of solid-ion density. [S0031-9007(98)07766-7]

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The pending development of ultraintense laser pulses will allow the study of new regimes of laser-matter interaction [1]. Lasers are now being designed [2] which will eventually lead to light intensities such that $I\lambda_\mu^2 \gg 10^{19}$ W $\cdot$ μm^2/cm^2. Here I is laser intensity of the laser light and λ_μ is the wavelength in microns. At such intensities the electron jitter velocity in the laser electric field becomes relativistic: $p_0/mc > 1$, where p_0 is jitter momentum, m is electron rest mass, and c is light speed. When such lasers interact with an overdense plasma it has been shown that a large number of relativistic superthermal electrons are produced. Numerical simulations with the particle-in-cell (PIC) codes [3] show that as much as half of the absorbed laser energy goes into these superthermal electrons whose characteristic kinetic energy $E_{\rm hot}$ is roughly given by

$$E_{\rm hot} \approx \left[\sqrt{\left(1 + \frac{I\lambda_\mu^2}{1.4 \times 10^{18}}\right)} - 1\right] mc^2. \qquad (1)$$

Hence $E_{\rm hot} > mc^2$ for $I\lambda_\mu^2 > 4 \times 10^{18}$. In addition, extremely intense magnetic fields with strengths up to 250 MG are observed to form in the overdense plasma. Such strong fields help to confine the superthermal electrons in the lateral directions. For even higher $I\lambda_\mu^2$, we expect $E_{\rm hot}$ to exceed the pair production threshold. It is the purpose of this Letter to explore the physics of this regime and consider the prospects of creating a copious pair source many orders of magnitude more intense than currently available electron-positron sources in the laboratory.

Nonthermal electron-positron plasmas are known to be abundant in many astrophysical environments from pulsars to quasars. In the last few years discoveries of intense broadened 511 keV annihilation features lasting from days to weeks from several galactic black hole candidates [4] in our own Galaxy suggest that steady state thermal pair plasmas may also exist. Since pairs annihilate on very short time scales, to maintain a steady state plasma over such long times the pairs need to be created prolifically to balance the annihilation rate. Such thermal plasmas represent a new state of matter with unique thermodynamic and radiative properties drastically different from ordinary plasmas [5]. If we define "compactness" [5] roughly as the total plasma heating rate divided by its physical size, then for high compactness the pairs are primarily created by gamma ray (photon-photon) collisions. For low compactness cases the pairs are primarily created by charged particle (lepton-ion) interactions whose cross section goes up as the square of Z, the ion nuclear charge. Whereas in the astrophysical contexts we are often dealing with the high compactness case [5], in the laboratory sample estimates show that we will always be dealing with the low compactness case even for micron size laser spots. Hence in the following we will concentrate on pair production with high-Z targets (e.g., Au, $Z = 79$). For low compactness and a confined thermal plasma, Bisnovaty-Kogan, Zeldovich, and Sunyaev (BKZS) [6] first showed that there exists a fundamental limiting temperature above which there is no pair equilibrium since the pair production rate will always exceed the annihilation rate. This limiting temperature was found to be about $20mc^2$ for pure hydrogen. For high-Z or high-B plasma [7] it is expected to be lower but above the pair production threshold of $2mc^2$. If we use Eq. (1) as a measure of the superthermal electron temperature we find that formally, above a laser intensity of 10^{20} W/cm^2, the superthermal temperature would exceed the BKZS limit. In practice, the BKZS limit does not apply due to the short duration of a laser pulse since it assumes a steady state. What all this means is that above a certain laser intensity, pair processes must become important. We need to perform a time-dependent kinetic calculation to estimate the correct pair density development.

Consider a situation in which a significant fraction of the superthermal electrons and pairs are confined and reaccelerated to relativistic energies according to Eq. (1). In practice this can be accomplished by using a double-sided laser illumination so that the superthermal electrons and pairs are confined by the laser ponderomotive pressure in the front and back and by the strong magnetic fields on the side. In the limit of low annihilation rates the pair density grows according to

$$\dot{n}_+ = \dot{n}_{ei} + \dot{n}_{ee} + \dot{n}_{e\gamma} + \dot{n}_{\gamma\gamma} + \dot{n}_{\gamma i}\,, \qquad (2)$$

where the first term is the lepton-ion pair production rate, the second term the lepton-lepton pair production rate, the third term lepton-photon pair production rate, the fourth term the photon-photon pair production rate, and the fifth term the photon-ion pair production rate (here photons include bremsstrahlung and Compton upscattered gamma rays). We have estimated in detail the relative magnitudes of the five terms in Eq. (2). It turns out that for typical laser target environments the first term is by far dominant, at least until the pair density starts to dominate the ion density. For example, for $E_{\rm hot} = 5$ MeV, we find that the ratios of the above five terms are given approximately as follows. $\dot{n}_{ei} : \dot{n}_{ee} : \dot{n}_{e\gamma} : \dot{n}_{\gamma\gamma} : \dot{n}_{\gamma i} = 3 \times 10^{32} : 3 \times 10^{30} : 3 \times 10^{29} : 6 \times 10^{29} : 5 \times 10^{31}$, where we have used formulas from Ref. [8] and assumed that the gamma-ray density is given by relativistic bremsstrahlung of the superthermal leptons (Ref. [9]). Hence in the pair deficient regime Eq. (2) reduces to

$$\dot{n}_{+} \approx \dot{n}_{ei} = (n_{+} + n_{-})\langle n_i f v \sigma_{ei} \rangle, \tag{3}$$

where n_i is ion density, $n_{-} = n_{+} + Zn_i$ is total electron density, v is relative velocity between ions and leptons, and σ_{ei} is cross section for pair creation in the ion rest frame. The bracket denotes averaging over the normalized lepton distribution function f. At lepton energies much above threshold the cross section assumes the form [8]

$$\sigma_{ei} = 1.4 \times 10^{-30} Z^2 (\ln \beta\gamma)^3, \tag{4}$$

where γ is the lepton Lorentz factor and β is of order unity. Equation (3) can be integrated to give the pair growth history:

$$n_{+} = Zn_i[\exp(\Gamma t) - 1]/2, \tag{5}$$

where the pair growth rate Γ is given by the integral

$$\Gamma = 2n_i c \int d\gamma \sigma_{ei} f (1 - \gamma^{-2})^{1/2}. \tag{6}$$

As we will see below, Γ is of the order of $0.1(n_{\rm Au})/{\rm ns}$, where $n_{\rm Au}$ is the gold atomic density in units of normal solid density of 6×10^{22} ions/cm^3, for laser intensity exceeding a few times 10^{19} W/cm^2.

Using PIC codes, we have simulated two-sided laser illumination of Au targets for various laser intensities. As discussed in Ref. [3] and references therein, particle-in-cell computer codes work by differencing Maxwell's equations for the electromagnetic wave associated with the laser and use the relativistically correct equation of motion to advance electrons and ions. Figure 1 shows the superthermal electron distributions for sample cases generated by such two-sided laser heating. Note that the electron temperatures attained are higher than what would be predicted from the standard ponderomotive potential scaling, typically found for these laser-plasma interactions [3]. This is due to the fact that the electron can gain energy from both sides of the foil, since we are using double-sided illumination. Using the superthermal electron distribution f generated by these PIC simulations in Eq. (6), we find the pair growth rate as a function of the laser intensity used in the simulation. This is plotted in Fig. 2. As we anticipated, Γ rises with laser intensity rapidly near threshold. But above a laser intensity of a few times 10^{19} W/cm^2, Γ increases only slowly with laser intensity due to the log dependence of the cross section, as shown in Fig. 3. An important implication of this result is that for a laser of given total energy, to optimize the pair production one should make the laser

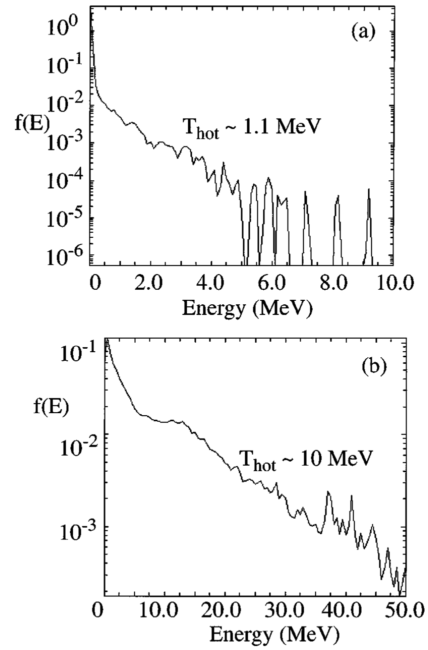

FIG. 1. (a) Electron distribution resulting from intense lasers ($I = 8.6 \times 10^{18}$ W/cm^2) heating a thin foil (3.5 μm thick, at density $n/n_{\rm cr} = 30$) from both sides. (b) Electron distribution function for same thin foil being heated by lasers with $I = 1.4 \times 10^{20}$ W/cm^2.

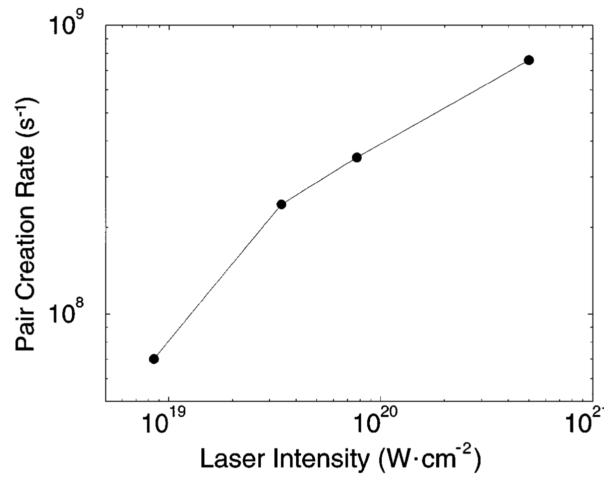

FIG. 2. Pair production rate Γ plotted as a function of laser intensity I. Dashed curve is just to guide the eye. At $I \gg 10^{20}$ W/cm^2 we expect the curve to level off due to the log dependence of pair production cross section on Lorentz factor γ. [Refer to Eq. (4).]

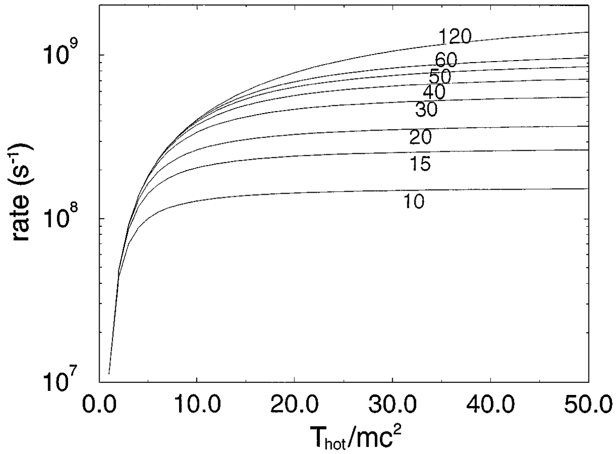

FIG. 3. Pair production rate Γ plotted as a function of the hot electron Maxwellian temperature $T_{\rm hot}$ for sample values of the upper Lorentz factor cutoff $\gamma_{\rm max}$.

pulse as long as possible provided the intensity stays above $\approx 10^{20}$ W/cm^2. A corollary is that the smaller the laser spot size the better. From Fig. 2 we see that for a 10^{20} W/cm^2 laser lasting 10 ps (such as that proposed for the faster ignitor or LLNL), $\Gamma t \approx 2 \times 10^{-3}$ and the pair density can in principle reach 0.1% of the target electron density. Since Γ is linearly proportional to n_i one obvious way to increase the pair creation rate is to precompress the target to densities much higher than solid density (e.g., with another laser) prior to hitting it with the high intensity laser.

Another relevant issue is the maximum number of pairs one can hope to achieve for a given laser pulse energy and whether we can ever reach a pair-dominated state, as in the case of BKZS [6]. Assuming that a typical pair carries a total (rest plus kinetic) energy of $4mc^2$, we find
kJ of laser energy, if 50% converted to superthermals and then a fraction p of that converted to pairs, will give rise to a total of $p \times 10^{14}$ pairs. This is to be compared to the total number of Au ions in a 10 μm diameter target spot of 1 μm thickness $= 5 \times 10^{12}$ and the total number of background electrons $= 4 \times 10^{14}$.

In addition to the confinement and reacceleration of the superthermal electrons and secondary pairs, we also need to consider their radiative cooling. This includes bremsstrahlung and synchrotron cooling. If these processes are on a much shorter time scale than the laser pulse, then the above discussions on pair density evolution needs to be amended. For a typical field of a few hundred megagauss and Lorentz factor of 10, we find that the synchrotron cooling time [9] is 10 ns, whereas the bremsstrahlung cooling time [9] is on the order of nanoseconds. Hence they are longer than the laser pulse if we are dealing with a sub-ns pulse. But if we eventually go to a much longer laser pulse scheme then the radiative losses must be included in estimating the pair production. In any case we find that the energy loss by the superthermals to bremsstrahlung will always be at least a factor of 10 or more larger than the loss to pair production. Hence the factor p in the above paragraph will always be less than 0.1. However, at sufficiently high compactness (large photon density) some of the bremsstrahlung gamma rays will be reconverted back to pairs via gamma-gamma collisions. Accurate estimates can be calculated only via detailed numerical simulations.

How does one diagnose the pairs and superthermals? The direct method is to measure the prompt bremsstrahlung and annihilation gamma-ray fluxes and spectra. However, many of the pairs will escape from the production region and annihilate in the surroundings (e.g., target chamber walls), likely after the laser pulse is over. Hence to estimate the total number of pairs produced we need to integrate the total 511 keV flux over durations comparable to positron flight times to the target chamber walls. On the other hand, the prompt bremsstrahlung gamma rays from the superthermals provide diagnostics about the superthermal flux and energies during the laser irradiation. Hence together they will serve to calibrate the above estimates of the pair production efficiency.

In summary, we expect that the next generation of ultraintense lasers, such as the one under development for the fast ignitor at LLNL, will be able to generate significant density of pairs under optimal conditions. A 10 ps, 10^{20} W/cm^2 laser hitting solid density gold foils on both sides can in principle produce peak pair density of the order of 10^{-3} of the target electron density. An alternative approach to achieving a clean pair-dominated plasma is to let the above plasma freely expand after laser turn off. Then, since the pairs are thousands of times less massive than the ions, they will expand much faster than the ions. After many e-foldings of expansion, the leading rarefaction front will be pure pairs, leaving the ions and background electrons behind. We will publish the plasma dynamics of such a "pair fire ball" and its potential applications to gamma-ray bursts at a later date.

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