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Swarm of ultra-high intensity attosecond pulses from laser-plasma interaction.

S. S. Bulanov[1,2], V. Yu. Bychenkov[2,3], K. Krushelnick[1], A. Maksimchuk[1], K. I. Popov[3], W. Rozmus[3]

[1] FOCUS Center and Center for Ultrafast Optical Science, University of Michigan, Ann Arbor, Michigan 48109, USA
[2] Institute of Theoretical and Experimental Physics, Moscow 117218, Russia
[3] Theoretical Physics Institute, University of Alberta, Edmonton T6G 2J1, Alberta, Canada
[4] P. N. Lebedev Physics Institute, Russian Academy of Sciences, Moscow 119991, Russia

Abstract. We report on the realistic scheme of intense X-rays and γ-radiation generation in a laser interaction with thin foils. It is based on the relativistic mirror concept, *i.e.*, a flying thin plasma slab interacts with a counterpropagating laser pulse, reflecting part of it in the form of an intense ultra-short electromagnetic pulse having an up-shifted frequency. A series of relativistic mirrors is generated in the interaction of the intense laser with a thin foil target as the pulse tears off and accelerates thin electron layers. A counterpropagating pulse is reflected by these flying layers in the form of a swarm of ultra-short pulses resulting in a significant energy gain of the reflected radiation due to the momentum transfer from flying layers.

The development of sources of intense ultra-short electromagnetic (EM) pulses, X-rays, and even γ-rays is an important potential application of intense laser matter interactions [1]. One of the most promising ways to generate such sources is the use of a reflection of EM radiation from a flying relativistic mirror. This was first studied by Einstein in [2] as an example of Lorentz transformations. The radiation frequency up-shift is proportional to the square of the mirror Lorentz factor, making the scheme very attractive for the generation of high frequency pulses.

The principal idea of the relativistic plasma mirror has existed for a long time [3]. Recently several ways to create such mirrors have been proposed. One way is to use the plasma waves in the wakefield of a high intensity pulse as it travels through low density plasma in the wave breaking regime [4, 5]. Another potential method is the interaction of intense linearly polarized electromagnetic pulses with solid density plasma, where either sliding [6] or oscillating mirrors [3, 7, 8, 9] can be formed. The relativistic mirrors can also be formed in the regimes of laser-thin foil interaction previously considered in regard with the ion acceleration [10, 11, 12, 13].

In this letter we propose a more realistic mechanism for generation of ultra-short EM pulses in laser-solid density target interaction. In the proposed scheme such pulses are created in the course of a counterpropagating laser pulse interaction with a series of flying electron layers, *i.e.* the Relativistic Multilayer Reflection (RMR) mechanism. Such layers are produced when an intense laser pulse interacts with a thin solid density target and extracts and accelerates thin electron layers [14, 15, 16, 17]. The high density and relativistic velocity of these electron layers make it possible that such structures will reflect the incoming radiation, acting as flying mirrors.

Let us first estimate the properties of the flying electron layers using a simple 1D model. Serial layer production occurs at the instants when the laser field is high enough to extract electrons from the foil, which attracts them back by the Coulomb force. Such values of the field are reached at consecutive maxima and minima of laser electric field. The number of electrons per flying layer can be obtained from the requirement that the Coulomb attraction force should be compensated by the Lorentz force exerted by the EM field on the electrons and the fact that each electron layer, escaping the attraction of the ion core, increases the charge separation field that should be compensated for by the laser pulse field [17]. Let us approximate the field of the laser as $a = a_0 \exp[-t^2/\tau^2]\cos[2\pi t/T]$, where τ is the half of the duration of the pulse and T is the period of the EM wave. The maxima and minima of such a wave are at $t_j = Tj/2$, $j = 0, \pm 1, \pm 2, ...$ Then for some field maximum a_j the charge separation field that already exists is determined by a_{j+1}. Then the number of electrons evacuated is $\Delta N_j^e = \lambda R^2 n_{cr}(a_j - a_{j+1})$, here R is the radius of the irradiated area. The total number of evacuated electrons will be $\Delta N^e = \sum_j \Delta N_j^e = \lambda R^2 n_{cr} a_0$, *i.e.* is determined by the maximum of the vector potential only. The duration of the bunch can be found by solving the equation $a(t_j + \xi_j) = a_{j+1}$:

$$\frac{\xi_j}{T} = \frac{1}{2\pi}\arccos\left\{\exp\left[-\frac{T^2}{\tau^2}\left(\frac{j}{2}+\frac{1}{4}\right)\right]\right\}. \quad (1)$$

For a laser pulse with $\tau = 5T$ and $T = 3$ fs the electron bunch has an attosecond duration: $\xi_0 = 60$ as, which is in good agreement with the results of 2D PIC simulations presented below.

In order to estimate the reflection coefficient of the flying electron layer we perform Lorentz transformation to the reference frame co-moving with the electron layer and use the results of Ref.[8]: reflection $\rho = \epsilon_j/(i + \epsilon_j))$ and transmission $(\tau = i/(i + \epsilon_j))$ coefficients. Here $\epsilon_j = \epsilon_0^j/(1+\beta)\gamma = \epsilon_0^j/2\gamma$ (since $\beta \sim 1$) is the parameter governing the transparency of the foil in the co-moving with the foil frame and $\epsilon_0^j = \pi \Delta n_j^e \xi_j / n_{cr} T$ is the transparency parameter of the electron layer in the laboratory frame [8]. For the incident laser intensity, I_0, the reflected pulse in the laboratory frame will have the up-shifted frequency by a factor of $4\gamma^2$ and the increased intensity and energy

$$I = \frac{16\epsilon_0^{j\ 2}\gamma^4}{4\gamma^2 + \epsilon_0^{j\ 2}} I_0, \qquad \mathcal{E}_r = \frac{4\epsilon_0^{j\ 2}\gamma^2}{4\gamma^2 + \epsilon_0^{j\ 2}} \mathcal{E}_0. \quad (2)$$

For $\gamma \ll \epsilon_0^j$ $\rho \to 1$ and reflected intensity and energy are determined by the Lorentz factor alone. In the second case, $\gamma \gg \epsilon_0^j$, the foil moves so fast that it becomes increasingly transparent for incoming radiation and the energy of the reflected pulse is limited by the transparency parameter $\mathcal{E}_r \sim \epsilon_0^{j\ 2}$. Thus the efficiency of the light intensification is determined by $\gamma^2 \times \min\{\gamma^2, \epsilon_0^{j\ 2}\}$ for intensity and $\min\{\gamma^2, \epsilon_0^{j\ 2}\}$ for energy.

Below we present the results of 2D PIC simulation using code REMP [20]. The targets are composed of fully ionized carbon C^{+6} with an electron density of $400 n_{cr}$. The grid mesh size is $\lambda/200$, space and time scales are given in units of λ and $2\pi/\omega$, respectively, the simulation box size is $15\lambda \times 12.5\lambda$, where λ and ω are high-intensity laser wavelength and frequency respectively. The number of particles per cell is 225. The 1.6 PW laser pulse which generates flying electron layers is introduced at the left boundary and propagating along x axis from left to right. The pulse is linearly polarized along the y axis (P-polarization), tightly focused ($f/D = 1$), and has Gaussian transverse and longitudinal profiles. The counterpropagating laser is introduced at the right boundary and propagates from right to left along the x axis. It is polarized along the z axis (S-polarization) in order to distinguish between the radiation generated by the accelerating pulse and the reflected one. It has $a_0 = 1$ and $\lambda_0 = 4\lambda$.

Below we present the results of 2D PIC simulations for the cases of a mass limited target and a thin foil (see Fig. 1). We consider the mass limited target to show the formation of flying electron layers without a transverse flow of electrons towards the irradiated spot. In the first case the counterpropagating laser pulse is reflected from the flying electron layers accelerated

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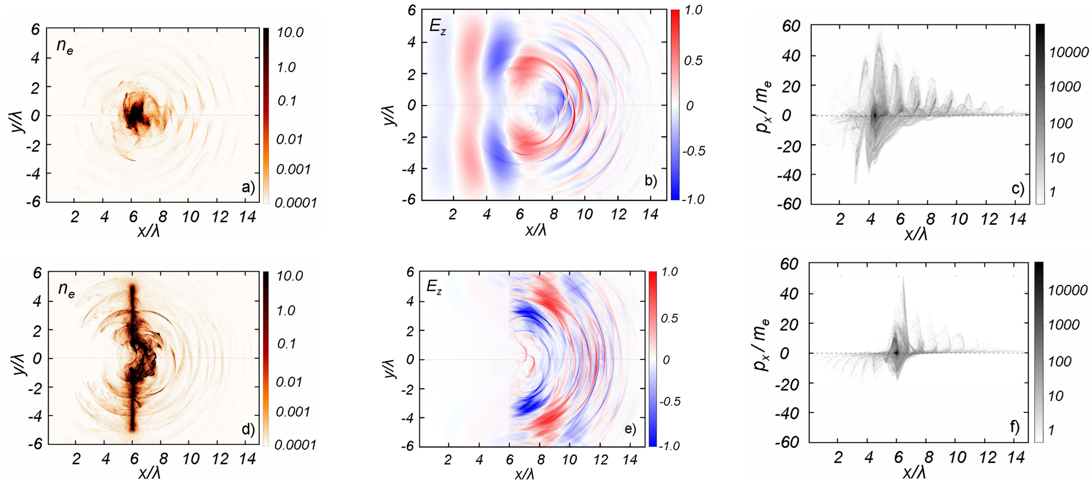

Figure 1. (color on-line)The reflection of laser pulse by accelerated electron layers in the case of a mass limited target (upper row: a, b, and c) and a thin foil (lower row: d, e, and f). The electron density distribution a) at $t = 20$ and d) at $t = 18$; the distribution of counterpropagating pulse electric field after reflection, b) at $t = 20$ and e) at $t = 18$, the field is measured in units of $m_e c\omega/e$; the distribution of electrons in (p_x, x) phase plane at $t = 12$, c) and f).

from a disk with diameter 1λ and thickness 0.1λ placed at $x = 6.0\lambda$, *i.e.* before the focus of the accelerating pulse, which is focused at $x = 8.0\lambda$ (Figs. 1a-c). In the second case the pulse interacts with a 0.1λ thick foil placed at the focus ($x = 6\lambda$) of the accelerating pulse. The electron density distributions at $t = 20$ are shown for both cases in Figs. 1a and 1d. The thin electron layers that act as flying relativistic mirrors can clearly be seen. The density of these layers vary from 5 to $15 n_{cr}$ for the mass limited targets and from 10 to $20 n_{cr}$ for the thin foil. The duration of these bunches is about 70 as. The distance between the layers is equal to λ in the half-spaces $y > 0$ and $y < 0$. At the same time the layers in $y > 0$ and $y < 0$ half-spaces are shifted by $\lambda/2$ in the x direction with respect to each other. The generation of swarms of short EM pulses through the RMR mechanism is demonstrated in Figs 1b and 1e. In order to determine the properties of flying electron layers and determine Lorentz factors of mirrors the distributions of electrons in (p_x, x) phase plane are shown in Figs. 1c and 1f for $t = 12$. The formation of flying relativistic mirrors with $\gamma \sim 5$ can clearly be seen.

Further intensification can possibly be achieved if we are able to focus the reflected pulse into a diffraction limited spot. Let us estimate the resulting intensity and possible applications to the study of QED effects in such fields. For a single pulse it will lead to

$$I_f \simeq (D/\lambda_r)^2 I = \begin{cases} 256\gamma^8 (D/\lambda_0)^2 I_0, & \gamma \ll \epsilon_0^j \\ 64\gamma^6 \epsilon_0^{j\,2} (D/\lambda_0)^2 I_0, & \gamma \gg \epsilon_0^j \end{cases} \qquad (3)$$

where D is the reflected pulse width before focusing and $\lambda_r = \lambda_0/4\gamma^2$. Then for $\epsilon_0^j \sim 10^2$, $\gamma \sim 10$, $D = 3\lambda_0$ and $I_0 \sim 10^{18}$ W/cm^2 the resulting intensity will be of the order of the intensity characteristic for the effects of nonlinear QED, *i.e.* Schwinger intensity, $I_S \sim 10^{29}$ W/cm^2, [18]. At this intensity the probability of one of the most profound processes of nonlinear QED, the e^+e^- pair production in vacuum by strong EM field, becomes optimal. We should note here that the plane EM wave does not produce pairs in vacuum [18], because in this case both field invariants, $\mathcal{F} = \mathbf{E}^2 - \mathbf{H}^2$, $\mathcal{G} = \mathbf{EH}$, are equal to zero, which is not the case for the focused pulse [19].

Let us estimate the threshold field (intensity) needed to produce one electron-positron pair by such a field in vacuum. Since the pairs are produced primarily near the focus, we take $\pi R^2 c\tau$ for the spatial volume of the pulse and estimate the number of pairs produced, according to [18], as

$$N \approx \frac{e^2 E_S^2}{4\pi^2 \hbar^2 c} \pi R^2 c \tau^2 \bar{\epsilon}\, \bar{\eta} \coth \frac{\pi \bar{\eta}}{\bar{\epsilon}} \exp\left(-\frac{\pi}{\bar{\epsilon}}\right), \tag{4}$$

here $\bar{\epsilon}$ and $\bar{\eta}$ are the averaged over time values of dimensionless field invariants $\epsilon = \sqrt{(\mathcal{F}^2 + \mathcal{G}^2)^{1/2} + \mathcal{F}}/E_S$ and $\eta = \sqrt{(\mathcal{F}^2 + \mathcal{G}^2)^{1/2} - \mathcal{F}}/E_S$ in the focus and have the meaning of electric and magnetic fields in the reference frame where they are parallel, see, e.g., Ref. [18]. Here $\mathcal{F}$ and $\mathcal{G}$, are the invariant of the electromagnetic field. In order to find $\bar{\epsilon}$ and $\bar{\eta}$ we utilize the results of Ref. [19], where a 3D model of electromagnetic field in focus [21] was used. Then $\mathcal{F}_e(0,0) = 4\Delta^2 E_0^2 g^2 \left(\frac{\varphi}{\tau}\right)$, $\mathcal{G}_e(0,0) = 0$, $\epsilon = 2\sqrt{2}\Delta g E_0$. Here $\Delta \equiv c/\omega R = \lambda/2\pi R$ and R is the radius of the focal spot. The intensity in this model is $I = G\frac{c}{4\pi}E_0^2$, $G = \sqrt{\pi/32}$ for $g = \exp(-4(t-z)^2/\tau^2)$. Then $\bar{\epsilon} = (128\pi)^{1/4} (I/I_S)^{1/2}\Delta$, $\quad I = (\bar{\epsilon}^2 I_S)/(8\sqrt{2\pi}\Delta^2)$. The average threshold field, i.e. the field that is needed to produce one electron-positron pair per pulse, is given by $\bar{\epsilon}_{th} = (\pi/\Lambda)(1 - 2/\Lambda \log(\pi/\Lambda))$, $\Lambda = 2\log\left[(c\tau\lambda)/(4\pi^2 l_c^2 \Delta)\right]$, here l_c is the electron Compton wavelength. Since the focus pulse an up-shifted frequency by a factor of $4\gamma^2$ and is compressed by the same factor, $\Lambda = 18$ for $\lambda_r = \lambda/4\gamma^2$, $\tau_r = \tau/4\gamma^2$, $\Delta = 0.1$ and $\gamma = 10$. Then $\bar{\epsilon}_{th} = 0.2$ and the intensity is $I_{th} = 9.7 \times 10^{28}\mathrm{W/cm}^2$.

As a conclusion, in this letter we considered a new way to generate ultra bright high intensity X-rays and γ-rays by reflecting EM pulse from the relativistic mirror. In the proposed scheme the role of the flying mirror is taken by laser accelerated electron layers, which are formed in the process of the intense laser pulse interaction with thin solid density targets. The reflected pulses have an up-shifted frequency and increased intensity. The reflected pulse intensification is determined by $\gamma^2 \times \min\{\gamma^2, \epsilon_0^{j\ 2}\}$. Further intensification of the reflected light can be achieved by its focusing into a diffraction limited spot that will bring the resulting peak intensity well into the domain of nonlinear QED with laser systems, which are presently available.

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