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Self-Thomson Backscattering of Ultra-Intense Laser from Thin Foil Target

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ABSTRACT

An electromagnetic solitary structure in attosecond regime is identified, costreaming with electron bunch. It is observed via nonlinear process of Self-Thomson backscattering of an ultra-intense laser from thin foil target. The process is termed as Self-Thomson Backscattering since the counter propagating electron sheets are generated by the drive laser itself. The radiation pressure acceleration model is considered for the interaction of a super-intense linearly polarized laser pulse with a thin foil in one-dimensional (1D) particle-in-cell (PIC) simulations.

Keywords: Ultra-Intense Laser Plasma Interaction; Thomson Backscattering; Solitary Electromagnetic Field

1. Introduction

The electromagnetic (em) solitary structures attract great deal of attention because they are of fundamental importance for nonlinear science [1,2] and are considered to be a basic component of turbulence in plasmas [3]. Thus, the numerical identifications of solitons, among the different kinds of coherent structures that are formed by an intense laser pulse in a plasma, stimulated a renewed interest in developing an analytical model and in envisaging ways of detecting solitons experimentally [4]. The em soliton [5] found in 1D and 2D simulations consist of slowly or nonpropagating electron density cavities inside which an em field is trapped and oscillates coherently with a frequency below the unperturbed plasma frequency and with a spatial structure corresponding to half a cycle.

Coherent structures, such as solitons (see [6] and references therein) and vortices, are fundamental features of this nonlinear interaction. Indeed, analytical and numerical results have shown that low-frequency, slowly propagating, subcycle solitons can be generated in the interaction of ultraintense ultrashort laser pulses with underdense plasmas. A significant fraction of the laser pulse energy can be trapped in these structures in the form of em energy. The typical size of these solitons is of the order of collisionless electron skin depth. The fields inside the solitons consists of synchronously oscillating electric and magnetic fields plus a steady electrostatic field which arises from the charge separation as electrons are pushed outward by the ponderomotive force of the oscillating fields.

The attosecond regime is of interest, not only for studies of atomic and molecular dynamics [7] but also for the generation of high fields and coherent X-rays [8]. High quality X-ray sources are requested in many fields of science. Presently, large free-electron lasers (FEL) [9] represent powerful coherent VU and X-ray sources, which open a new era of intense VUV or X-ray interaction with matter and provide unprecedented opportunities for research in condensed matter physics, high energy-density physics [10] and single biomolecular imaging [11]. High laser harmonics from gas targets [12] and relativistic laser plasma interaction [13] are also very useful and promising coherent X-ray sources. Such harmonic sources typically produce trains of sharp spikes separated by the time period of the driving laser pulse.

The PIC simulations study, of relativistic nonlinear optics in the regime of tight focus and ultrashort pulse duration (the λ^3 regime) explored that synchronized attosecond electron bunch and attosecond em pulse emerge efficiently from laser-overdense plasma interaction. In the λ^3 regime, the entire laser pulse energy is contained within a focal volume of few λ^3. The λ^3 concept enabled a more basic understanding and a more practical implementation of these phenomena because it provides a spatial and temporal isolation.

Bright and coherent X-ray sources can also be obtained by coherent Thomson scattering (CTS) from dense electron layers flying with relativistic factor $\gamma_x = 1\big/\sqrt{1-\beta_x^2}$. Here $\beta_x = v_x/c$ is the velocity of plane flyer in normal direction. Counter-propagating probe light is then mirrored and frequency-upshifted by the relativistic Doppler factor, which is $(1+\beta_x)/(1-\beta_x) \approx 4\gamma_x^2$ for $\gamma_x \gg 1$ [14]. Recently, it was found [15] that ultrashort dense electron sheets can be generated from ultrathin foils by intense laser pulse in the blow-out regime. In the blow-out regime, all foil electrons are separated from the ions and synchronously accelerated to relativistic energies forming a dense electron sheet. This sheet has extremely small thickness (a few nms), a near solid density and velocity close to c, so that it can be used as a relativistic electron mirror (REM). Such an extreme optics are suitable for coherent reflection of a second counter propagating pulse for frequency upshift, pulse compression and amplitude intensification. Since the REM is a transient coherent structure, in which all electrons move synchronously. It exists only for a limited period of time. Due to large Coulomb forces, the electrons in the left side of the REM turn back at some time while other electrons continue to move to right. While turning back, these electron sheets (which are counterpropagating to incident laser field) interact with restover incident laser field.

In this letter we focus on the reflection of incident laser pulse with the counterpropagating electron sheets (generated by the laser itself). We show that these electron sheets can be used as a near ideal REM for coherent reflection of incident pulse. We call this process as Self-Thomson Backscattering (STBS) since the incident pulse itself generates the REM and then these REMs reflect the restover laser field. We demonstrate the process of STBS with the help of 1D PIC simulation. We numerically show the scheme to observe the attosecond em solitary field via reflection of laser pulse with counterpropagating electron sheets, generated by the incident laser itself. An analytical radiation pressure acceleration model is considered for the dynamics of electron sheets generated from super intense laser irradiated ultrathin foil.

2. Modeling of Ultraintense Laser-Plasma Interaction

At first we carried out simulation using a fully relativistic 1D PIC code to demonstrate the process of STBS (**Figures 1** and **2**); we further delineated the reflected em-solitary field co-streaming with electron bunch (**Figures 3(a)** and **(b)**) in process of STBS. In our simulation a linearly polarized laser pulse with peak amplitude $a_0 = eE_0/mc\omega = 300$, $\lambda = 1$ μm and the duration 6 *fs* is normally incident on a thin foil of thickness $l_0 = 7$ nm and initial foil density $n_0 = 600n_c$ from time $t = 0$. The target boundary is located at $x = 50\lambda$ and the laser pulse impinges on it at $t = 100T$, where $T = \lambda/c$. We take 5000 particles per species per cell and cell size of $\lambda/1000$.

An ultra-relativistic strong laser pulse irradiates a thin foil with thickness l_0 and electron density n_0. In order to blow out all foil electrons, the laser ponderomotive force $(v/c)\times\boldsymbol{B} = \boldsymbol{E}$ has to larger than the maximum electrostatic field $E_{s,\max.} = 4\pi e n_0 l_0$ induced due to the charge separation. This means that the foil thickness l_0 should satisfy

$$\frac{l_0}{\lambda} \ll \frac{1}{2\pi}\frac{n_c}{n_0}a_0. \tag{1}$$

The PIC simulation results are shown in **Figure 1** to show the process of STBS without inclusion of RR. At $t = 49.0\text{T}$, two cycle linearly polarized laser pulse is shown in **Figure 1(a)**, before it hits the thin foil target. Due to strong radiation pressure, all electrons are quickly blown out, forming a dense electron sheet co-moving with the laser pulse. An electron depletion region is left behind which increases with time (**Figure 1(b)**). The charge separation field is uniform between the electron sheet and the slowly expanding ions while it steeply decreases within the sheet down to zero at the right surface. Because the sheet is much thinner than the skin depth as $l_0 \ll \lambda_s = c/\omega_p$, the pulse front is penetrating through the sheet with its electric field exponentially damped due to the energy transfer to electrons. These dense electron sheets have been used as near ideal REM to coherently reflect a counter propagating probe pulse for frequency upshifting and amplitude intensification. Because of the large Coulomb forces, the electrons on the left side of the REM turn back at some time while other electrons continue to move to the right side. Therefore the dense electron sheet can be considered as a coherent transient structure with a limited time duration. The life time of electron sheet depends critically on the parameter a_0 and the foil area density $n_0 l_0$. Since the space charge field is nonuniform in REM and it decreases linearly from the left side (close to ion sheet) of REM to the right. Hence the electron layers on extreme left of REM experience strong force due to space charge field and at some instant when this force becomes stronger than the longitudinal component of the Lorentz force of laser, the dense electron sheet (REM) start to debunch (**Figure 1(c)**). We obtain the attosecond electron bunch counterpropagating to incident laser, as a result of debunching of the REM. We focus in this letter to explore the interaction of these attosecond left turning back (LTB) electron sheets with the rest over counter propagating incident laser pulse. Since the LTB electron sheets are accelerating due to both Coulomb interaction among the the electron sheets and Coulomb interaction between the electron sheets and the ion background of the target as shown in **Figure 1(d)**. We see (as shown in **Figure 1(e)**) attosecond electron bunch co-streaming with the em solitary field of attosecond length after the

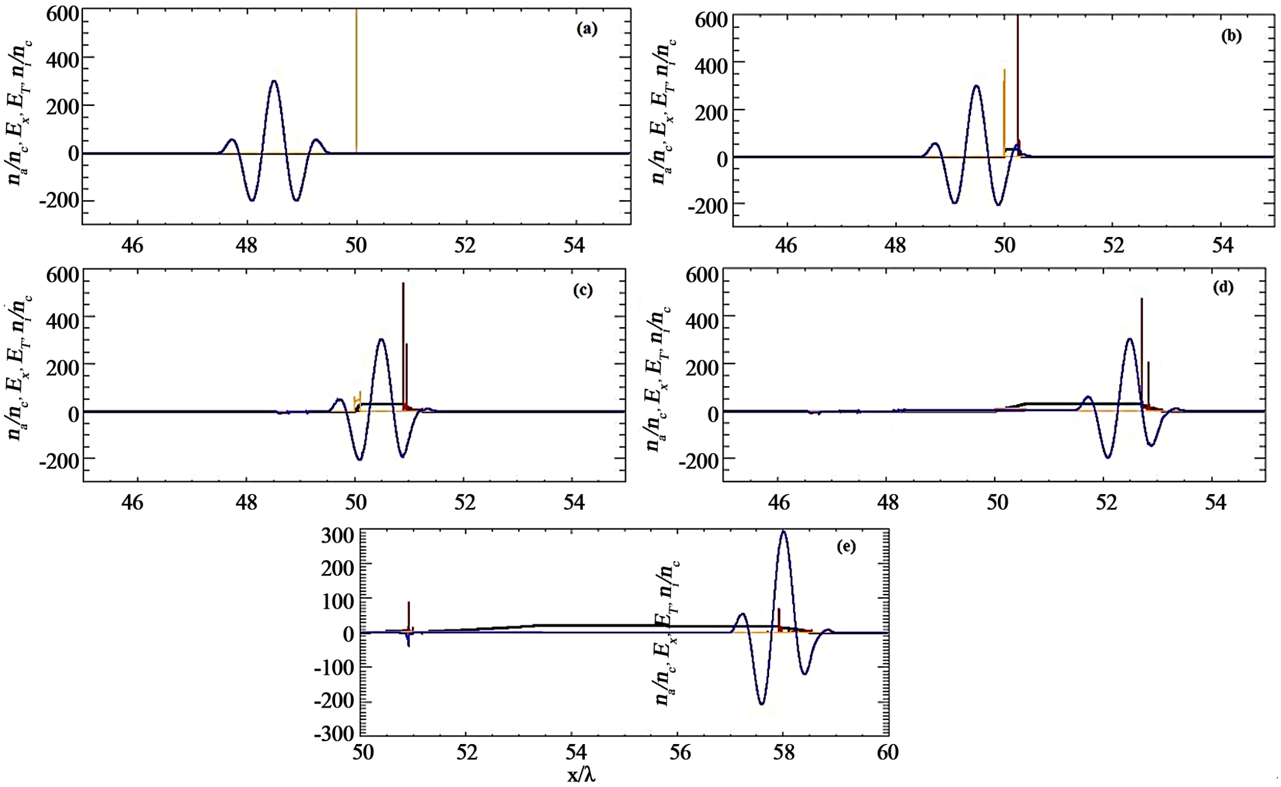

Figure 1. (Color) 1D PIC simulation for the demonstration of the whole scheme: electron density n_e/n_c (red), ion density n_i/n_c (yellow) laser field, E_y (blue), charge separation field E_x (black), for foil with initial density $n_0 = 600n_c$ and initial foil thickness $l_0 = 7\ \text{nm}$ irradiated by *y*-polarized laser at amplitude $a_0 = 300$ and wavelength $\lambda = 1\ \mu\text{m}$. (a) The blue solid line shows that the drive laser field E_y, before it hits the foil (red solid line) at $t = 49.5\text{T}$; (b) A uniform space charge field E_x sets up between the electron sheet (solid red line) and slowly expanding ions (solid yellow line) at $t = 50.5T$ as laser pulse propogates through the target; (c) At $t = 51.5\text{T}$ electrons on the left side of REM start to move due to large Coulomb force; (d) At $t = 53.5\text{T}$ acceleration of left turning back (LTB) electron sheets due to both coulomb interaction among the electron sheets and coulomb interaction between the electron sheets and the ion background as time increases; (e) At $t = 59.0\text{T}$ after the reflection of attosecond electron bunch with restover drive laser field, an attosecond electron bunch is observed costreaming with em solitary field of attosecond lngth.

reflection of LTB electron layer from restover drive laser field.

We explain further the generation of attosecond electron bunch as a consequence of debunching of REM in this 1D model, where a wave normally incident on an abrupt thin plasma target. The ponderomotive force from the incident and reflected waves acts on electrons within the skin depth. Therefore, electrons from the skin layer are thrown toward the bulk of the plasma. At the same time, there is counterpropagating electrons from the bulk plasma in the direction of the skin layer due to the attractive force towards ions that were left behind by the inward-driven electrons and by the repulsive force of those electrons. Hence, due to stronger (in camparison to Lorentz force which drives electrons from skin layer in to plasma) space charge field counterstreaming of electrons occurs. The velocity of the counterstreaming electrons is relativistic (as shown in **Figure 2**). While leaving the plasma with relativistic velocities, these LTB electron bunch interacts with restover drive laser field and compress the reflected radiation. We observe the reflected radiation in form of attosecond em solitary structure while LTB electron layers maintain their attosecond structure (as shown in **Figure 1(e)**).

3. Simulation Results

The results of numerical simulation of the acceleration of electron bunch with the thickness $l_0 = 7\lambda/1000$ are illustrated in **Figure 2**, which shows the evolution of longitudinal (**Figure 2(a)**) and transverse momenta (**Figure 2(b)**) calculated for $a_0 = 300$. This value of dimensionless laser field amplitude a_0 corresponds to an ultra relativistic electromagnetic pulse, in which electrons are already accelerated to relativistic energies over a time interval much shorter than the period of

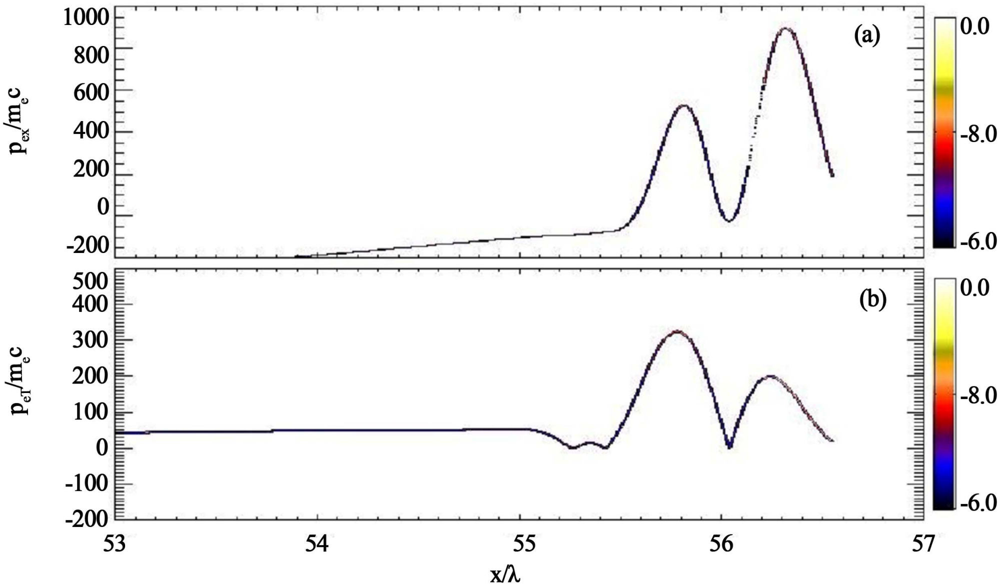

Figure 2. (Color) The variation of the longitudinal momentum $p_{ex}/m_e c$: (a) And transverse momentum $p_{eT}/m_e c$; (b) Of electrons at $t = 50.7\text{T}$. Numerical parameters are same as in Figure 1.

external wave. As soon as an electron is accelerated to a relativistic velocity, the amplitude of the Lorentz force decreases significantly in accordance with the Doppler transformation, so that the accelerating forces subsequently have essentially no impact on the motion of the electron, which thus experiences only Coulomb forces and the forces that compress the electron bunch. The Coulomb attractive force exerted by the target ions on the electrons act to reduce the longitudinal electron momentum p_{ex}. Then the external field reverses polarity and the process repeats itself. Note that during, the next-half period, the compressing force becomes weaker, so that the Coulomb forces break the bunch up into parts: the Coulomb repulsive forces between the electron sheets reverse the direction of motion of the sheets closest to the ion background and continue to accelerate the farthest sheets; as a result, the bunch is actually break up in ultrashort electron bunch sheet (called earlier LTB).

In the process of acceleration of the electron bunch, the Coulomb forces of repulsion between the electron sheets in the bunch play an important role. Actually, if the ion background is absent, these forces can blow up the bunch in a very short time. This is the main difference. The situation is not so bad for the acceleration of electron bunches by ultrarelativistic $(a_0 \gg 1)$ laser pulses because in that case, there are forces that compress the bunch along the x-axis and partially compensate for the Coulomb forces, thus supporting initial geometry of the bunch. These compressing forces arise due to the radiation reaction force. At the initial stage of acceleration the compressing force can be large enough to counterbalance the Coulomb forces during the first half-cycle. In this case, the electron bunch can survive for several periods, depending on the value of $\alpha = \pi\left(\omega_p^2/\omega^2\right)\left(l_0/\lambda\right)$. In the case of a larger pulse amplitude a_0 or a smaller value of the parameter α, the time of stability will be larger.

Let us now demonstrate the reflection of drive laser field by LTB electron layers using the 1D PIC code. The LTB electron sheets hit the rest over drive laser pulse at $t = 53.5\text{T}$ as shown in **Figure 1(d)**. In **Figure 3(a)**, we see the em solitary structure due to the interaction of counter propagating LTB electron sheet with incident laser field at the point $t = 70\text{T}$. The amplitude of the reflected em field is the result of interference between the waves scattered by different electrons in the relativistic mirror.

A further proof of the STBS process discussed above is provided here for a target of thickness $l = 10\ \text{nm}$ in **Figure 3(b)** and other parameters are same as in **Figure 1**. We identify in this case also the em solitary structure comoving with electron bunch on attosecond scale because of debunching of REM and then counterstreaming electron bunch interaction with restover drive laser field. By increasing the thickness we keep control on the space charge field. The electrons initially co-moving with laser field sooner starts to counterpropagate due to decrease of longitudinal component of the Lorentz force in comparison to space charge field. We observe the effect of increased space charge field as shown in **Figure 3(b)** that shows more intense and shorter em field in comparison to the case as shown in **Figure 3(a)**.

4. Conclusion

In conclusion, we investigate a new approach to generate

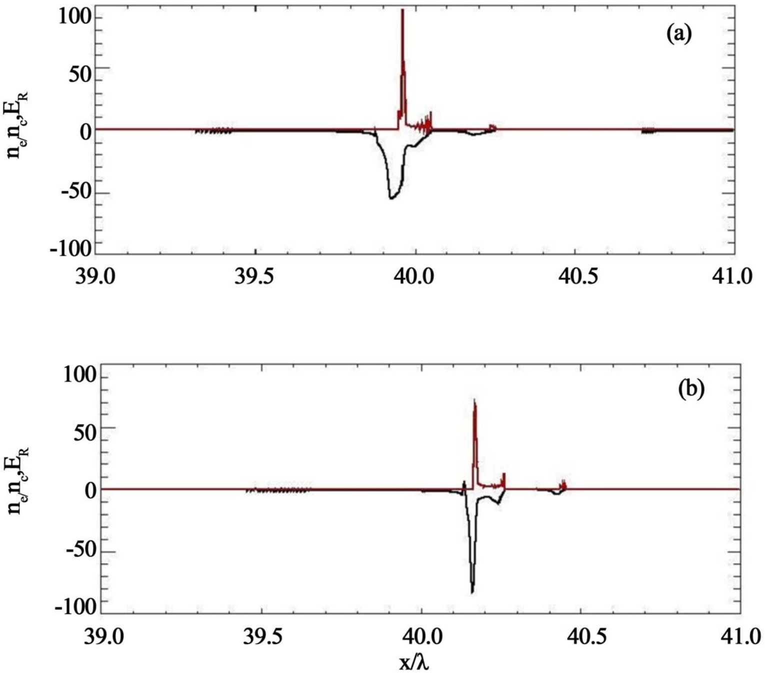

Figure 3. Identification of costreaming attosecond em solitary field E_R (black) and electron bunch n_e/n_c (red) at $t = 70.0T$, for linearly polarized laser pulse. The PIC simulation parameters are same as in Figure 1.

the attosecond electron bunch via debunching of REM. We identify the intense ultrashort em solitary field co-streaming with attosecond electron bunch through the process of STBS. The spatail distribution of the solitary field, together with attosecond LTB electrons is found to be dependant upon the laser-plasma parameters.The radiation pressure acceleration model is considered for the interaction of a super-intense linearly polarized laser pulse with a thin foil in one-dimensional (1D) PIC simulations. We also conclude in this investigation that the details of reflected em field may change due to radiation reaction effects or quantum effects. For example, even at the level of $10^{22}\ \mathrm{W/cm^2}$, the total losses could be on the order of a percent with respect to the incident laser energy. Taking in to account these losses concern only a small group of the fastest particles, radiation reaction effects may be considered at such high intensities.

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