Theoretical investigation on novel particle beams and radiation sources in relativistic laser-solid interactions

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Abstract. We report the recent theoretical and numerical studies of quasi-monoenergetic electron and proton beams in laser solid interactions, where the quasi-monoenergetic electrons are produced in laser interaction with wire-targets and the quasi-monoenergetic protons are produced by ultra-intense circularly polarized laser pulses in a new acceleration regime called phase-stability acceleration. For the generation of coherent radiation at high frequencies, attention is paid on the emission from electron plasma waves excited in a thin solid target.

1. Introduction

There is increasing interest in generating quasi-monoenergetic electron and protons beams by use of ultrashort intense laser pulses. For quasi-monoenergetic electron beam generation, the scheme by use of high-amplitude laser wakefields in tenuous plasma have been investigated widely [1]. However, to our knowledge, the possibility to produce quasi-monoenergetic electron bunches in laser-solid interaction has not been paid sufficient attention. In the laser interaction with solid wire and/or slice targets, we demonstrate that dense quasi-monoenergetic electron bunches can be produced directly by laser ponderomotive-force acceleration [2], provided the transverse dimensions of the solid wire and/or slice targets are less than a laser wavelength. Such electron bunches are suitable for applications in compact injector of accelerators, compact high-brightness sources of X-ray radiation, and ultrafast electron diffraction imaging, etc.

In laser solid interaction, usually one obtains proton beams with a large energy spread. For many applications, it is desirable to have quasi-monoenergetic proton bunches as well. It was proposed that quasi-monoenergetic protons can be obtained with a double layer targets, when a thin layer containing protons (having the highest charge-to-mass ratio) is attached behind the first layer [3]. When the laser
intensity is high enough and with a high contrast ratio, a collisionless electrostatic shock wave is driven, which can accelerate some protons inside the target to twice of the shock speed [4]. When a solid target is thin enough, a new acceleration regime called phase-stability acceleration can occur, which enables one to obtain a few MeV protons with 100TW lasers.

In laser solid interaction, surface high harmonics generation is supposed to be a promising coherent X-ray source. It can also be used to generate attosecond pulses when a suitable frequency filter is adopted since the high harmonics are found to be phase locked. The mechanism for the high harmonics generation is supposed to be the surface oscillation of the solid target driven by the incident laser pulse [5]. We suggest another mechanism to produce high frequency emission by exciting an electron plasma wave inside the solid target. The electron plasma wave can be driven by the electron bunches produced by the incident ultrastrong intense laser pulse.

2. Generation of quasi-monoenergetic electron bunches

For the laser interaction with a wire/slice target, the laser propagates along the target extent. The electrons are accelerated by the ponderomotive force of a relativistic intense laser pulse directly during its interaction. The mechanism is studied both analytically and by multi-dimensional PIC simulations [2]. In the following, we show typical results obtained by using 2D PIC simulations. The wire target is a thin uniform plasma strip with width $D=0.1\lambda_0$ (in the y-direction) and length $L=5\lambda_0$ (in the x-direction). The incident laser has a Gaussian profile transversely with a beam waist of 2$\mu$m and it propagates along the wire or slice target as plotted in figure 1(a).

Figure 1(a) shows a snapshot of electrons emitted from the slice target in 2D space. Electrons near the peak of transverse laser field are pulled out from the target to vacuum and are accelerated by the $V\times B$ mechanism. The positive laser field peaks pull electrons toward the negative y-direction and the negative fields pull electrons toward the positive y-direction. Since both positive and negative peaks are separated by one laser wavelength in space, the emitted electrons appear as separated bunches both upside and downside. The trajectories of selected electrons are given in figure 1(b). They show that
electrons are expelled from the target surface by the laser pulse. Some trajectories appear similar to the ponderomotive force scattering in vacuum. Note that these energetic electrons usually emit with a small angles against the x-direction.

It shows that the obtained energy spectrum has a quasi-monoenergetic peak around 11MeV as shown in figure 1(c). For comparison, we have also simulated the interaction of the same laser pulse with a plasma slice with a transverse width $D=20\lambda_0$. The resulting electron energy spectrum shows an exponential distribution as usually seen. Even though the quasi-monoenergetic electron beams are found with wire or slice target with the laser pulse propagating along the wire axis, such electron beams can be found in the laser interaction with plane targets with a geometry such as in figures 1(d) and 1(e). For the case as in figure 1(e), the incident angle should be large such as over 70 degree.

3. Generation of quasi-monoenergetic proton bunches in the phase stability regime

In this scheme, the protons are generated from an ultrathin foil irradiated by an ultraintense laser with circular polarization in a regime called the phase stability acceleration (PSA) alike in the traditional RF linac. In this regime the charge separation field $E_z = 4\pi en_0L > (v_x B_y / c) \sim E_x$, where $B_y$ and $E_x$ are the transverse fields of the laser, $n_0$ and $L$ are the initial plasma density and the thickness of the solid target. Thus the required laser power is still less than in the laser-piston regime [6]. In the proposed PSA regime, the charge separation field and ponderomotive force are balanced around the laser peak amplitude. Because the laser pulse is circularly polarized in our case, the electrons in the thin target are compressed into a small region and only a part of electrons are displaced. As the dynamic equilibrium between both forces exists, the ion beam can be synchronously bunched and accelerated by the electrostatic field all the time during the laser interaction [7]. The output beam in this regime has a very low energy spread like in the conventional radio frequency accelerator.

Figure 2 displays typical simulation results. The output proton beam reaches the energy about 375MeV. Moreover, the proton beam has an awfully lower FWHM energy spread (< 4%) and high ion intensity. We have developed an analytical theory, which agrees well with the numerical simulation.

![Figure 2](image)

Figure 2. (a) Schematic of the equilibrium density profiles of the ion $n_i$ and the electron $n_{e0}$. The x position at $x=d$ indicates the electron front, there laser evanescence starts and it vanishes at $x=d+l_s$, where $l_s$ is the plasma skin depth; Plots (b) and (c) show the phase space distribution and energy spectrum of protons, respectively, found after an acceleration time of 200 laser cycles with the laser pulse at a normalized laser peak amplitude $a_0=0.5$ and duration $100\tau_0$ and the plasma slab with the initial density $n_{e0}/n_e=10$ and thickness $L=0.2\lambda_0$.

4. Generation of broadband coherent emission from laser-solid interaction

It is well known that electromagnetic and electrostatic waves can convert into each other under certain conditions, which is so-called linear mode conversion. It leads to the resonance absorption of light in
plasma when a laser light is incident obliquely onto an inhomogeneous plasma. Its inverse process also exists. For example, in inhomogeneous underdense plasma, a laser wakefield can convert into terahertz radiation [8]. Recently such a process is also found in laser-solid interaction, where emission at high harmonics of the laser frequency was observed [9]. We have re-investigated the problem of mode conversion in laser-solid interaction. It shows that broadband coherent emission can be produced by exciting electron plasma waves in a thin solid target, the latter are driven by fast electron bunches. The emission frequency corresponds to the electron plasma frequency of the target.

Figure 3 presents an example result from PIC simulations, where an inhomogeneous plasma density distribution such as in figure 3(a) is adopted. We take the following parameters for the incident laser pulse $a_0=0.5$ and $\tau=4\tau_0$. Typically, the reflected light pulse is composed of two part. The first part is made of the reflected pulse at fundamental frequency and its high harmonics, where the high harmonics are known to be produced by front surface oscillation. The corresponding frequency spectrum is shown in figure 3(b). The second part is found at later time, which is emitted from the electron plasma waves excited inside the overdense plasma region via the linear mode conversion. The spectrum plotted in figure 3(c) shows broad distribution located between $\omega/\omega_0=2$–3, which is relevant with the initial electron density distribution of the plasma target.

**Figure 3.** (a) Initial plasma density adopted in the simulations; (b) Emission spectrum of the first part of the reflected light pulse; (c) Emission spectrum of the second part of the reflected light pulse. The incident pulse has the parameters: $a_0=0.5$, $\tau=4\tau_0$, at the incident angle $\theta=29.5^\circ$.

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