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Review article

Collimated gamma rays from laser wakefield accelerated electrons

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Abstract

Betatron radiation from laser wakefield accelerated electrons and X-rays scattered off a counter-propagating relativistic electron bunch are collimated and hold the potential to extend the energy range to hard X-ray or gamma ray band. The peak brightness of these incoherent radiations could reach the level of the brightest synchrotron light sources in the world due to their femtosecond pulse duration and source size down to a few micrometers. In this article, the principle and properties of these radiation sources are briefly reviewed and compared. Then we present our recent progress in betatron radiation enhancement in the perspective of both photon energy and photon number. The enhancement is triggered by using a clustering gas target, arousing a second injection of a fiercely oscillating electron bunch with large charge or stimulating a resonantly enhanced oscillation of the ionization injected electrons. By adopting these methods, bright photon source with energy over 100 keV is generated which would greatly impact applications such as nuclear physics, diagnostic radiology, laboratory astrophysics and high-energy density science.

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Keywords: Laser wakefield accelerator; Gamma ray; Hard X-ray; Betatron radiation; Enhancement

1. Introduction

As a noxious co-product of the electron accelerators in its early years, synchrotron radiation has now dominated science and industry worldwide. The synchrotron light sources provide X-ray pulses with the merits of tunable energy, high brightness, good collimation and polarization, etc., which make synchrotron radiation a premier choice to probe the structure and dynamics of matter. Despite the unprecedented capability as a research tool, the accelerator based light sources are still developing rapidly towards ultrashort (femtosecond) pulse duration, higher energy (hard X-ray) and higher brightness. Representing the state-of-art light source, the X-ray free electron lasers (XFEL) could deliver coherent X-rays with peak brightness ten orders of magnitude to the 3rd generation light sources, enabling accurate pump-probe measurement of matter in extreme conditions. To meet the enormous need from science community and industry, currently many countries are

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developing the fourth generation light source and almost all 3rd generation sources are being upgraded or planned to be upgraded.

Though going through fast expansion, the limited access to these giant machines will definitely slow the pace of science and compromise the quality of research. To reduce the cost and shrink the large scale facility into a university laboratory scale system would benefit scientific researchers all over the world. As complementary methods, compact X-ray light sources (CXLS) would fill the capability gaps in multi disciplines. For this purpose, several CXLS schemes or concepts were proposed and studied. Among those schemes, light sources based on a compact storage ring [1,2] or a conventional undulator [3] are combination of optical methods and conventional accelerator technologies. More concise schemes are based on a laser plasma accelerator (LPA) [4,5] which was first proposed by Tajima and Dawson in 1979 [6]. And LPAs based state-of-the-art X-ray FELs are under extensive study, the discipline has been discussed and several mechanisms have been proposed [1−3]. After development over three decades, different LPA regimes have been proposed and investigated extensively, keeping pace with the available laser systems, i.e. plasma beat wave accelerator (PBWA) [4,5], laser wakefield accelerator (LWFA) [6], self-modulated laser wakefield accelerator [7,8]. However, currently, most LPAs are now working in the so called "bubble" regime [7,8] in which an intense femtosecond laser pulse expels the electrons off the axis of propagation, forming an electron-free cavity which then capture and accelerate electrons to GeV range [9,10]. Lu et al. [9] pointed out that, in the high intensity limit ($a_0 \geq 4$), the bubble will be driven efficiently when the laser spot size r_0 satisfies $k_p r_0 \approx 2\sqrt{a_0}$, while the plasma wave simply presents a sinusoidal form in the mildly relativistic regime, where k_p is the wavenumber of electron plasma wave and a_0 the normalized laser vector potential. In all optical schemes, the laser plasma accelerated electrons are wiggled either in the ion cavity itself (betatron radiation) or in a counter-propagating laser pulse (relativistic Thomson backscattering or Inverse Compton Scattering, ICS), emitting synchrotron radiations like X-rays with approximately the same pulse duration to the drive laser pulse (20−40 fs). Besides the low cost, compactness, micron scale source size and ultrashort pulse duration, these two methods could deliver photons with energy extending to the gamma ray range, this is beyond the reach of the conventional synchrotrons and distinguishes them from the laser driven high harmonic generation (HHG) source which up-converts the laser to extreme ultraviolet (EUV) or soft X-ray regime [11]. Another feature of betatron and ICS source is that the radiation is highly directed, which is different from the case of Kα source [12−14] and LPA based bremsstrahlung [15]. The Kα source typically diverges over all space and the LPA based bremsstrahlung source has a divergence angle of a few degrees (FWHM), while betatron and ICS sources have typically a few mrad. Naturally synchronized with the drive laser pulse along with all the merits mentioned above, betatron and ICS sources are very promising for many interesting applications, including pump-probe study of ultrafast chemical, biological process [10,11], industry and defense sectors [12]. For more detailed applications, we refer the reader to the review of Chen et al. [13].

Two critical factors of the light source for application are the operation energy range and photon flux. We have been studying laser driven secondary sources for decades with laser systems of different scale and parameters, and have achieved progress in enhancing the betatron radiation both in photon energy and flux recently. By using a clustering gas jet, direct laser acceleration (DLA) mechanism is stimulated, causing much more electrons to be accelerated and wiggled with large amplitude, hence more photons are emitted [16]. Another method to achieve large charge and wiggle amplitude is to trigger a continuously injected electron bunch through the laser and bubble evolution [17,18]. Finally, the electron transverse oscillation could also be enhanced via the ionization injected electrons resonating with the drive laser pulse [19]. These progresses make laser based betatron radiation more efficient and pave the way for applications.

In this article, we review the betatron radiation and ICS sources from laser plasma accelerators in Section 2. As radiation originated from accelerated charge, they are analogous to the synchrotron radiation. In Sections 3, 4 and 5, we summarize our recent progresses in betatron enhancement.

2. All optical LPA based collimated gamma ray sources

2.1. Radiation of a relativistically moving electron

In the framework of classical electrodynamics, the very essence of betatron radiation and ICS is just like the synchrotron radiation. In order to characterize the radiation features of betatron and ICS, the radiation of a relativistic moving electron is reviewed briefly. Consider an electron moving relativistically ($\gamma \gg 1$) in an arbitrary orbit $\boldsymbol{r}(t)$, the radiated energy per unit solid angle and per unit frequency interval is [20].

$$\frac{\mathrm{d}^2 I}{\mathrm{d}\omega \mathrm{d}\Omega} = \frac{e^2}{4\pi^2 c}\left|\int_{-\infty}^{\infty} \frac{\boldsymbol{n}\times\left[(\boldsymbol{n}-\boldsymbol{\beta})\times\dot{\boldsymbol{\beta}}\right]}{(1-\boldsymbol{\beta}\cdot\boldsymbol{n})^2}\exp\{\mathrm{i}\omega[t-\boldsymbol{n}\times\boldsymbol{r}(t)/c]\}\mathrm{d}t\right|^2. \quad (1)$$

Here $\boldsymbol{n}$ is the direction of observation, $\boldsymbol{\beta}$ and $\dot{\boldsymbol{\beta}}$ are the velocity and acceleration which could be derived from a known $\boldsymbol{r}$ (t). It shows clearly that the acceleration is essential for radiation. More detailed analysis shows $P \propto \boldsymbol{F}_{\parallel}^2$ and $P \propto \gamma^2 \boldsymbol{F}_{\perp}^2$ [21], i.e., transverse force ($\boldsymbol{F} \perp \boldsymbol{\beta}$) is much more efficient for driving this radiation. The radiation features are directly linked to the electron orbit, which results in two distinct regimes depending on the relationship of the radiation opening angle ($1/\gamma$) and the maximum angle (θ_{max}) of the trajectory to the propagation axis. When $\theta_{max} \ll 1/\gamma$, the radiation from different parts of the trajectory is directed along the propagation axis, corresponding to the undulator regime; When $\theta_{max} \gg 1/\gamma$, the other regime called wiggler regime dominates. Now a very important parameter called strength

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