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Estimation of Smith-Purcell Radiation in Laser-plasmas Interaction

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Abstract. We present an estimation of Smith-Purcell Radiation by electrons generated in laser-plasmas interaction, passing near a metallic grating surface. The radiation wavelengths change with different grating periods and emission angles. The output photon numbers are also estimated. This effect could be developed into a new kind of tuneable table-top radiation source and also a diagnostics for the electron transport in over-dense plasmas.

1. Introduction

Smith-Purcell Radiation (SPR) was first observed by Smith and Purcell in 1953 by electrons passing over a periodic metallic grating surface [1]. It attracted interests because SPR offers a possibility of a compact tunable radiation source and a diagnostic method of electron source. Many experiments have been done to observe SPR from millimeter to visible light range [2-6]. However, most of these experiments were performed with electrons produced by accelerators, which can produce ultrahigh energy (up to near GeV), small emittance (several $\pi$ mm mrad) beams with low energy spread (<1%). SPR in far-infrared region was also observed by using the beam of a scanning electron microscope, which is capable of generating a continuous, small divergence, 20-40 keV beam with a total current $\leq$1mA. Many theoretical explanations also have been given to characterize the emission process. In van den Berg’s theory, the incident and diffracted electromagnetic fields were expanded in terms of Fourier integrals and infinite matrix equations with a matching of boundary conditions at the metallic grating surface [7-9]. Another theory was called surface current model, which considered the surface charge induced on the grating by the electron beam passing over and dragged along with it [10, 11]. Both these theories have their own advantages while the results were quite similar.

As we mentioned before, most of the experiments were carried on electron accelerator facilities. These facilities are of big size and expensive. However, as the development of ultrashort high power laser technologies over the past years, energetic particles such as fast electrons, high-energy ions, and neutrons have been generated in laser-matter interactions. Recently, monoenergetic beams of relativistic electrons have been observed from laser wakefield accelerator [12-14]. By special designed plasma devices, we can successfully guide and collimate high density MeV electrons [15, 16]. With these techniques, controllable electron beams with high quality can be obtained in laser-plasma interaction. These features give us a chance for the development of a “table-top” tunable SPR radiation source.
2. Calculation and estimation

An electron bunch passing close to the surface of a metal grating, as in Figure 1, emits SPR at a wavelength $\lambda_n$ given by

$$\lambda = \frac{l}{n} \left( \frac{1}{\beta} - \cos \theta \right)$$

where $l$ is the grating period, $\theta$ is the emission angle with respect to the electron propagation direction, $\phi$ is the azimuth angle, $n$ is the harmonic order, and $\beta = \frac{v}{c}$ is the velocity of the electron bunch. The angular distribution of SPR power is given by

$$\frac{dP}{d\Omega} = N_g e^2 \beta^3 \sin^2 \theta \cos^2 \phi \left( 1 + N_e f(\sigma, \theta) \right) \exp \left\{ -\frac{4\pi \eta |\beta| \sqrt{1 + (\gamma \beta \sin \theta \sin \phi)^2}}{\gamma (1 - \beta \cos \theta)} \right\} |R_n|^2$$

where $N_g$ is the number of grating periods, $I$ is the beam current, $e$ is the charge of an electron, $\varepsilon_0$ is the permittivity of free space, $N_e$ is the number of electron per bunch, $b$ is the height of beam above the grating, $\gamma$ is the relativistic factor $\left(1 - \beta^2\right)^{-1/2}$, $(1 + N_e f(\sigma, \theta))$ is the coherence term, and $|R_n|^2$ is grating efficiency factor.

For radiation at wavelength shorter than the electron bunch length, the radiation is considered as incoherent. However, at wavelength longer than the bunch length, the radiation is coherent and the radiation intensity is enhanced. For a Gaussian distribution electron bunch, the coherence term can be assumed as

$$1 + N_e \exp(-k^2 \sigma^2 \cos^2 \theta)$$

where $k$ is the wave factor, $\sigma$ is the bunch length.

To estimate the radiation in laser plasma interaction, we used typical table-top laser parameters based on our p-cube Ti:sapphire laser system, which provide an output energy of 800 mJ, with a pulse duration of 60 fs, and a focal spot size of ~6 $\mu$m ($>10^{18}$W/cm$^2$). The mean electron temperature ($T_e$) is estimated to be about 1.5 MeV. We assume 280 mJ laser energy to chamber area, 40% in focal spot, and 20% is transfer to electron energy. The total electron number ($N_e$) per shot is about $1\times10^{11}$. A Maxwell distribution is used to build up the electron spectra, as shown in Figure 2.
For a simple estimation, we ignored the coherence term and the grating efficiency effect. For a radiation at the azimuth angle $\phi=0$, the equation 2 was simplified to

$$\frac{dP}{d\Omega} = N \frac{e ln^2 \beta}{2 l e_0} \frac{\sin^2 \theta}{(1 - \beta \cos \theta)^3} \exp\left(-\frac{4\pi p b}{\gamma l(1 - \beta \cos \theta)}\right)$$

(4)

We assumed those electrons travel 10 $\mu$m close and parallel to grating surface. And two typical types of grating periods (1200 lines and 830 lines) were chosen. The SPR spectra of different emission angle to the grating surface were calculated as Figure 3.

**Figure 3.** The calculated SPR spectra of different emission angle and grating period. The radiated photon numbers increase rapidly as the increase of electron energy. For those electrons with lower energy, the emission wavelengths were longer and the SPR efficiency is very low. The more energetic electrons emitted shorter wavelength radiation with higher efficiency. However, for electron energy higher than several MeV, the emission wavelengths reached to a cut-off and the output photon numbers still increased rapidly. For electrons over 9 MeV, the emission photon numbers reached to a maximum at a wavelength of $\lambda_M$ and started to reduce as the decrease of electron number.
\( \lambda_M \) were changing for different grating period and emission angle. For a grating period of \( l=1.2 \mu m \) (830 lines/mm), \( \lambda_M \) of SPR with emission angles \( \theta=95^\circ \) to 85\(^\circ \) changed from 1.3 \( \mu m \) to 1.1 \( \mu m \) in the short-wave infrared region. For \( l=0.83 \mu m \) (1200 lines/mm), \( \lambda_M \) with emission angles \( \theta=95^\circ \) to 85\(^\circ \) were from 1 \( \mu m \) to 800 nm, in the near infrared region. The maximum output photon numbers at the wavelength \( \lambda_M \) were calculated to be about \( 10^5-10^5 \) per solid angle.

3. Conclusion and discussion

We estimated the SPR generated in intense laser interaction with plasmas. In our simple calculation, we could expect different radiation wavelengths by choosing different grating periods and emission angles. This offered us an opportunity to develop a tuneable table-top radiation source.

The emission photon numbers were also calculated while we ignored the coherence effect and grating efficiency. According to others’ work, the grating efficiency might reduce the output power several orders depend on emission angle and grating type. However, the existence of small electron bunch in laser-plasmas interaction has already proved by other methods like optical transition radiation. This should result in a coherent SPR, which would have a remarkable enhancement of the radiation power. On the other hand, SPR could also be a powerful diagnostic method for electrons transport in over-dense plasmas.

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