Enhancement of Smith–Purcell radiation with surface-plasmon excitation*

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With the aid of a three-dimensional particle-in-cell code simulation, the enhancement of Smith–Purcell radiation with a surface-plasmon mode excited by a single electron bunch and by a premodulated electron beam is considered in the paper. In the simulation, the model is a grating covered by Ag film. The results demonstrate that when the surface-plasmon mode is excited by a single electron bunch, the maximum radiation occurs at an observation angle depending on the surface-plasmon frequency, and the radiation power can be enhanced more than ten times. And for pre-bunched electron beam excitation, when one of the harmonics of the bunching frequency is resonant with that of the surface-plasmon mode, the radiation power is twenty times more than that from a perfectly conducting grating excited by the same premodulated electron beam.

Keywords: surface plasmon, Smith–Purcell radiation, enhancement

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1. Introduction

When a charged particle passes close to the surface of a metallic grating, it emits Smith–Purcell diffraction radiation.[1,2] The corresponding wavelength, λ, within the radiation range is determined by

$$\lambda = -\frac{D}{m}(\beta^{-1} - \cos\theta), \tag{1}$$

where D is the grating period, c is the speed of light, βc is the electron velocity, m is the space harmonic, and θ is the angle between the observed radiation and the direction of motion of the charged particle, respectively. The Smith–Purcell radiation can produce electromagnetic radiation in a large frequency range, i.e., from the millimeter-wave to visible light regime, and is becoming of extensive interest in some potential applications, such as low-cost tunable high-power devices. In 2011, Jin *et al.*[3] carried out the experimental validation of the near-infrared radiation emission around 1000 nm, which was realized by coupling a periodic grating surface to the energetic electron bunches generated by the interaction between an intense and ultrashort pulse laser and plasma.

In the optical region, the permittivity of Ag or Au is a complex number, and the surface-plasmon mode is excited when the electron beam moves closely above the surface of the metal.[4,5] The enhancement of Smith–Purcell radiation from a grating excited by the surface-plasmon mode is studied in Ref. [6]. However, in Ref. [6] the periodic changes are neglected and there is no computer simulation.

In the present paper, by means of a three-dimensional (3D) particle-in-cell code simulation, the enhancement of Smith–Purcell radiation from a grating with surface-plasmon mode excitation is investigated in detail. Firstly, the simulation for a single electron bunch is carried out, and the results show that the Smith–Purcell radiation is enhanced more than ten times and have a certain radiation angle. Then, we simulate that a pre-bunch electron beam excites the grating, the radiation is enhanced greatly, more than twenty times when one of the harmonics of the bunching frequency is resonant with that of the surface-plasmon mode.

2. Simulation for Smith–Purcell radiation excited by a single bunch

To study the enhancement of Smith–Purcell radiation from a grating with surface-plasmon excitation,

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we use two models, as shown in Fig. 1. Model 1 is a perfect conducting grating (perfect electrical conductor, i.e. $\varepsilon_M = -\infty$), and Model 2 is an Ag film on the perfect conducting grating. In order to highlight the effect of the surface-plasmon mode, we assume the thin Ag film in Model 2. The period of the grating is $D = 200$ nm, the width of the groove is $a = 100$ nm and the depth of the groove is $h = 40$ nm. The parameters of Model 2 are the same as those of Model 1, except a 20-nm thickness Ag film in Model 2.

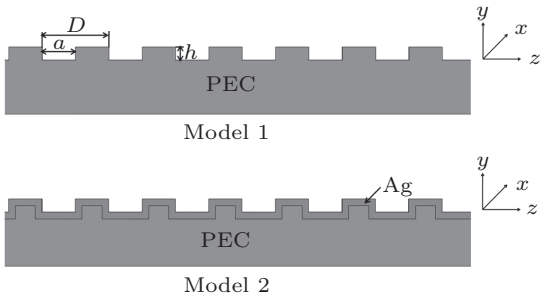


Fig. 1. Model 1 is a perfect conducting grating and Model 2 is a perfect conducting grating covered with Ag film (the permittivity of Ag can be expressed as a complex number using Drude model).

As for the perfect conducting grating, when the electron moves above and parallel to the grating, the surface wave will be excited on the grating surface because of the periodic changes of the structure. It is in fact a local field, propagating along the surface and decaying exponentially at the normal of the grating. Based on the theories in Refs. [7]–[10], the frequency of the excited surface wave depends on the point of the intersection between the dispersion curve and the electron beam line. In general, the surface wave excited by electrons lies in the non-radiation region, and the frequency of the surface wave is always below the threshold for Smith–Purcell radiation. Therefore, we cannot observe that the surface wave enhances the Smith–Purcell radiation.

The permittivity of metal is assumed to be a complex number following the Drude model in optical region. When an electron beam moves above a metallic grating, the surface-plasmon mode can be excited on the surface of the metal.[11,12] The frequency depends mainly on the electron energy and the metal characteristics. When the groove depth of the grating is very small compared with the period, the dispersion character can be described approximately as

$$k_z = \frac{\omega}{c}\left(\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1+\varepsilon_2}\right)^{1/2} = k_{\rm sp}, \tag{2}$$

where ε_1 and ε_2 are the permittivities of air and metal, respectively. The modified Drude model is adopted for Ag,[13] we obtain $\varepsilon_2(\omega) = \varepsilon_\infty - \omega_{\rm p}^2/(\omega^2 - {\rm i}\gamma\omega)$, with $\omega_{\rm p} = 1.39 \times 10^{16}$ rad/s, $\gamma = 3.2 \times 10^{13}$ Hz, and $\varepsilon_\infty = 5.3$.

The phase-matching condition for one of the Floquet waves with the surface-plasmon mode is given by[6]

$$\frac{c}{u_0} = \left(\frac{\varepsilon_1\varepsilon_2(\omega)}{\varepsilon_1+\varepsilon_2(\omega)}\right)^{1/2}, \tag{3}$$

where c is the velocity of light in vacuum and u_0 is the velocity of moving electrons. When the radiation angular frequency ω satisfies Eq. (3), the surface-plasmon mode can be excited.

When the surface-plasmon mode is excited by electrons and the maximum radiation appears, the observation angle of the maximum radiation should satisfy the relation

$$\cos\theta = \beta^{-1} + \frac{m\lambda}{D}, \tag{4}$$

where λ is the radiation wavelength. Since the main part of Smith–Purcell radiation comes from the -1 space harmonic radiation, we always assume $m = -1$. The frequency of the surface-plasmon mode can be larger than the threshold for Smith–Purcell radiation. Therefore, the maximum radiation will appear, with the observation angle θ satisfying Eq. (4), and the peak frequency is equal to that of surface-plasmon mode. The Smith–Purcell radiation of the grating of Ag (Drude model) in the optical region is analysed in Ref. [14] using the finite-difference time-domain (FDTD) method; the surface wave and surface-plasmon wave will be excited by electrons, and will radiate at the end of the grating. However, the surface-plasmon mode frequency cannot satisfy Eq. (4) in Ref. [14], thus the enhancement of the Smith–Purcell radiation will not be studied.

Firstly, the simulations of Smith–Purcell radiation excited by a single bunch are performed for the two models. The driving electron bunch parameters are listed as follows: the energy is 100 keV, the length of the electron bunch is 60 nm, the charge quantity of the electron bunch is 4×10^{-17} C (Coulomb), and the distance between the electron bunch and grating surface is 20 nm. When the electron bunch becomes closer to the grating surface, the strength of the incident wave of the electron bunch will become stronger

on the grating surface, and accordingly the surface plasmon excited by the bunch would be stronger. Figure 2(a) shows the contour map of H_x for Model 1 (the perfect conducting grating) and it is a typical Smith–Purcell radiation, where the -1 space harmonic is the main source of radiation. In order to compare the simulation results of the two models, we use the same electron bunch in the simulation, and the colour ratios are also the same in the contour maps of the two models, the colours can demonstrate the intensities of the radiations directly. Figure 2(b) shows the contour map of H_x for Model 2 (perfectly conducting grating covered by a thin Ag film). The intensity in Fig. 2(b) is much stronger than that in Fig. 2(a), and the radiation direction can be observed easily. This phenomenon is ascribed to the surface plasmon excited in Model 2. The frequency of the surface-plasmon mode is 756 THz in simulation, and the expected radiation angle is $\theta_1 = 100°$, which is in good agreement with the angle (labeled in dot line) shown in Fig. 2(b). The frequency of the surface plasmon of an Ag grating structure in simulation is not exactly equal to that of a flat structure, because the grating will shift the surface-plasmon frequency. Therefore, by covering an Ag film on perfectly conducting grating, the moving electrons can excite surface plasmons, the maximum

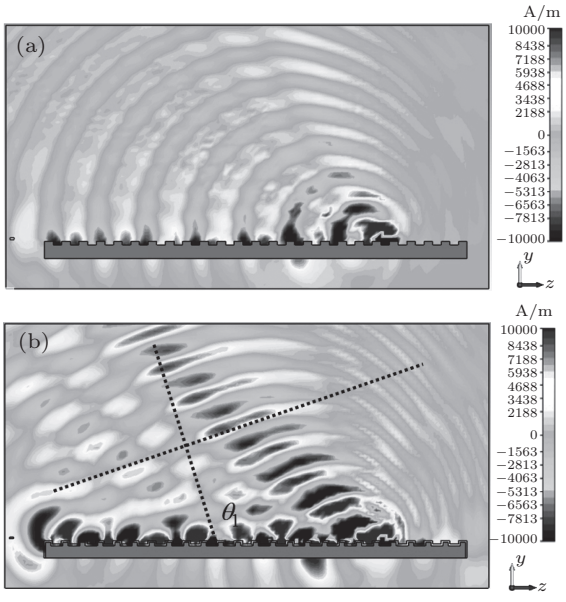


Fig. 2. Smith–Purcell radiation excited by a single bunch of 100 keV, showing (a) the contour map of transverse magnetic fields for Model 1, and (b) the contour map of transverse magnetic fields for Model 2.

radiation would appear, and the Smith–Purcell radiation is enhanced. In addition, we should point out that the radiation angle θ_1 is determined by the frequency of the surface-plasmon mode.

In order to study the enhancement of Smith–Purcell radiation quantitatively, the E_z detector is placed at the 10-period distance above the surface of the grating. The fields of the points in the two models are given in Fig. 3, along with the corresponding fast Fourier transform (FFT). The characteristics of the radiation are as follows. (i) Figure 3(a) is the time domain of the electric field for Model 1, and the frequency of the radiation wave changes from high to low based on Eq. (1). The -1 space harmonic is a main source for the Smith–Purcell radiation and its radiation band corresponds from 526 THz to 1818 THz, as shown in Fig. 3(b). (ii) The time domain of the electric field for Model 2 is given in Fig. 3(c). As for the observation point, the angle (θ) between the observed radiation and the direction of motion of the charged particle varies from 0° to 180°, the value of λ keeps longer based on Eq. (1), so the high frequency wave passes through the observation point first, and then so does the low frequency wave. When the frequency is equal to that of the surface-plasmon mode, the amplitude of the electric field is enhanced obviously. This is due to the surface-plasmon mode enhancing the Smith–Purcell radiation. Figure 3(d) shows the frequency spectrum of the electric field for Model 2, the highest frequency corresponds to the frequency of the surface-plasmon mode. For a high velocity electron bunch, the higher-order ($m = -2, -3, \ldots$) radiating waves contribute significantly to the radiated power in the (–1)st order radiating wave.[2,15] Here, the corresponding frequencies of the (–1)st order radiation wave are 526 THz–1818 THz, the corresponding frequencies of the (–2)nd order radiation wave are 1062 THz–3637 THz, and the corresponding frequencies of the (–3)rd order radiating wave are 1593 THz–5455 THz. Therefore, there are three obvious radiation bands in Fig. 3(d). (iii) By comparing the results in Figs. 3(a) and 3(c), we can find that by covering Ag film on the grating, the amplitude of the electric field is enhanced three times than that only for perfect conducting grating.

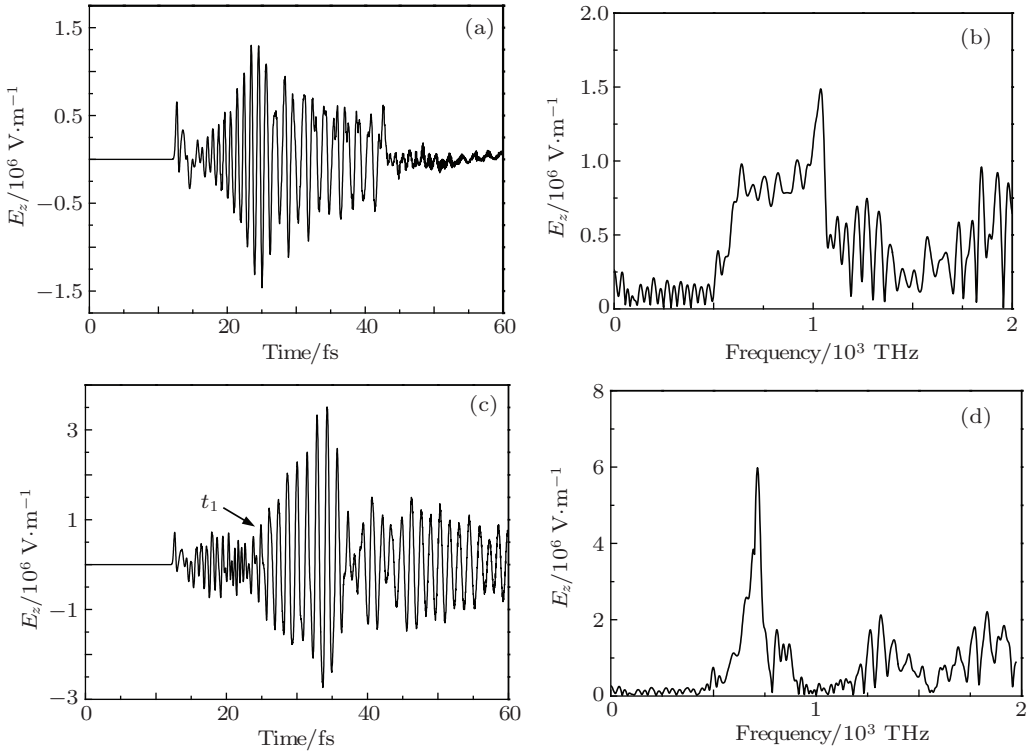


Fig. 3. Temporal behaviours of E_z and their corresponding FFT, showing (a) the time domain of the electric field for Model 1, (b) the frequency spectrum of the electric field for Model 1, (c) the time domain of the electric field for Model 2, and (d) the frequency spectrum of the electric field for Model 2.

As mentioned above, the surface-plasmon mode is the main reason for the enhancement of the Smith–Purcell radiation. Here, we will study the angle of the maximum radiation as the next step. In order to carry out this study, we assume that the plasma frequency of the Ag ($\omega_{\rm p}$) changes from 1.39×10^{16} to 1.6×10^{16}. In this case, the frequency of the excited surface-plasmon mode will increase. Because the frequency of the surface-plasmon mode increases to 830 THz in simulation, the angle will reduce to $\theta_2 = 88°$ based on Eq. (4). The angle shown in Fig. 4 accords well with the theoretic expectation.

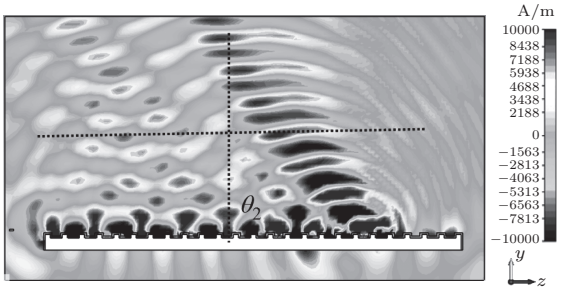


Fig. 4. Contour map of transverse field for Model 2 excited by an electron beam of 100 keV, showing that angle θ_2 is smaller than θ_1 in Fig. 2(b) because the frequency of the surface-plasmon mode increases.

The simulation results also confirm that the enhancement starting time (t_2) shown in Fig. 5 will be earlier than that (t_1) in Fig. 3(c), because the frequency of the surface-plasmon mode increases and the higher frequency wave will pass through the observation point earlier.

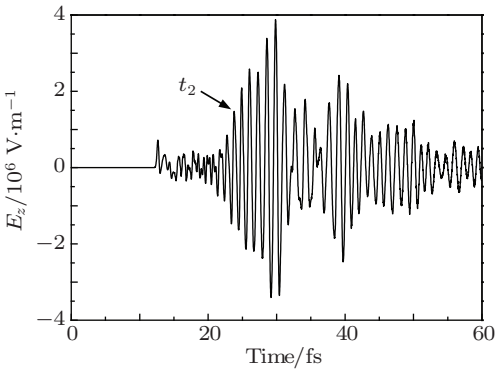


Fig. 5. Time domain of the radiation field with a peak frequency of 830 THz.

3. Simulation for Smith–Purcell radiation excited by a modulated current

Consider a premodulated current traveling above and parallel to a grating, and the occurrence of the strong emission of radiation, which is called superradiant radiation.[15,16] The radiation develops spec-

trally and angularly narrow peaks at the harmonics of the bunching frequency.[17,18] In order to avoid the buildup of beam bunching from an initially continuous beam, we use a train of periodic bunches to excite coherent and superradiant Smith–Purcell radiation in our simulation. The repetition frequency of bunches is set to be f and this frequency is below the threshold for Smith–Purcell radiation. However, the bunching is sufficiently strong so that higher harmonics are clearly visible in the beam current. These harmonic frequencies correspond to allowed Smith–Purcell radiation, as shown in Fig. 6. For the perfect conducting grating covered by a thin Ag film (Model 2), the Smith–Purcell radiation can be enhanced greatly when one of the harmonics of the bunching frequency is resonant with the surface-plasmon mode, and the radiation power is twenty times more than that for a perfect conducting grating (Model 1) excited by the same premodulated electron beam.

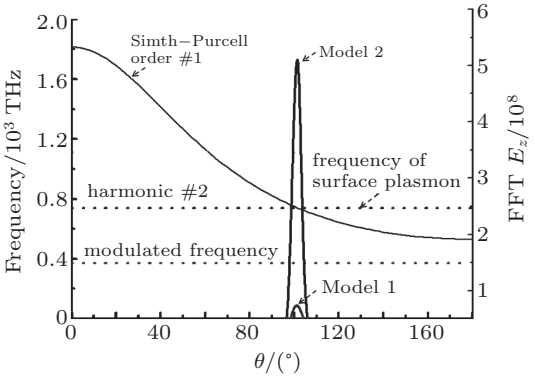


Fig. 6. Amplitudes of the major FFT coefficients each as a function of angle. The frequency of the first order Smith–Purcell radiation as a function of angle, together with the fundamental frequency of the modulated current, second harmonic are also shown. Model 1 and Model 2 are both excited by a modulated current (100 keV).

There are two plots given in Fig. 7. Figure 7(a) shows the superradiant effect for Model 1, and Fig. 7(b) displays the radiation for Model 2. The intensity of E_z in Fig. 7(b) is 5 times more than that in Fig. 7(a). The colour ratios are also the same in the contour maps of the two models so that the colour can demonstrate the intensity of the radiation as shown in Fig. 8. From the contour plots, one can easily understand why the intensity of radiation for Model 2 is much stronger than that for Model 1. The radiation angle can be observed clearly and accords well with the angle shown in Fig. 6.

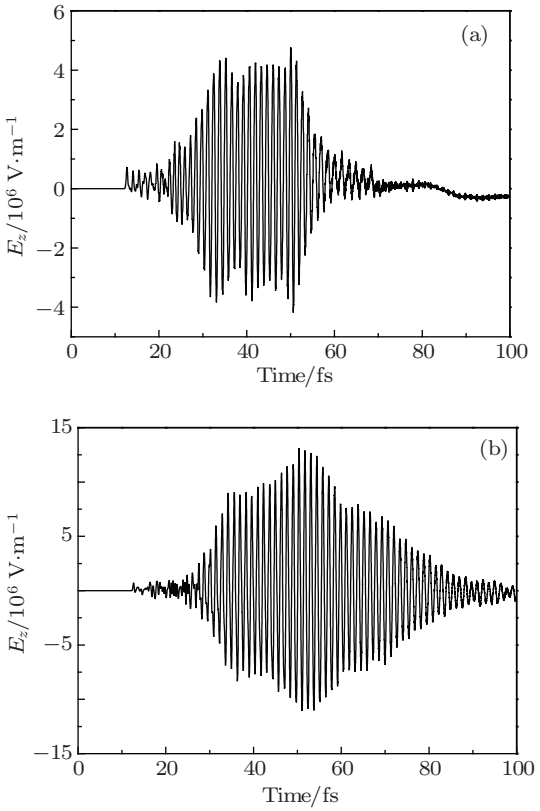


Fig. 7. Temporal behaviours of the electric field (E_z) of the super-radiant effect for Model 1 (a) and Model 2 (b).

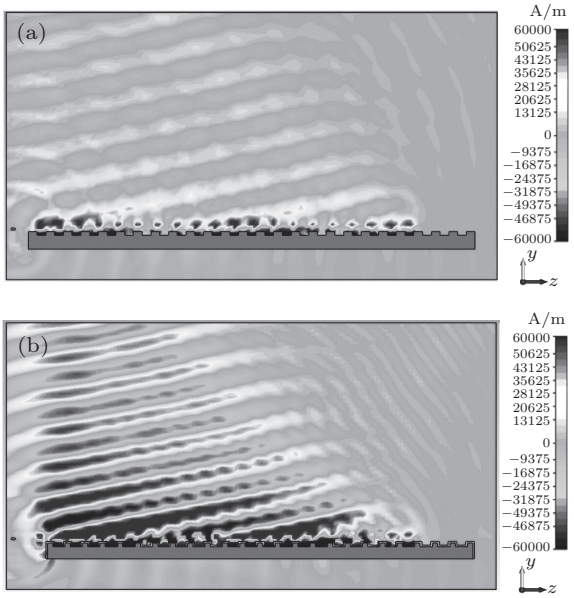


Fig. 8. The Smith–Purcell radiation excited by a train of bunches of 100 keV: (a) the contour map of H_x for Model 1; (b) the contour map of H_x for Model 2.

4. Conclusion

The enhancement of Smith–Purcell radiation from a grating covered by Ag film is numerically studied. In the simulation, the surface plasmon was taken

into consideration for two different kinds of electron beam excitations. When the surface-plasmon mode is excited by a single bunch, the radiation power can be enhanced more than ten times and the maximum radiation occurs at an observation angle, depending on the surface-plasmon frequency. For pre-bunched electron beam excitation, when one of the harmonics of the bunching frequency is resonant with the surface-plasmon mode, the radiation power is twenty times more than that from a perfect conducting grating excited by the same premodulated electron beam.

References

[1] Smith S J and Purcell E M 1953 *Phys. Rev.* **92** 1069

[2] van den Berg P M 1973 *J. Opt. Soc. Am.* **63** 689

[3] Jin Z, Chen Z L, Zhuo H B, Kon A, Nakatsutsumi M, Wang H B, Zhang B H, Gu Y Q, Wu Y C, Zhu B, Wang L, Yu M Y, Sheng Z M and Kodama R 2011 *Phys. Rev. Lett.* **107** 265003

[4] Ritchie R H 1957 *Phys. Rev.* **106** 874

[5] Sarid D 1981 *Phys. Rev. Lett.* **47** 1927

[6] Chuang S L and Kong J A 1984 *J. Opt. Soc. Am.* A **1** 672

[7] Andrews H L and Brau C A 2004 *Phys. Rev. Special Topics* **7** 070701

[8] Liu S G, Hu M, Zhang Y X, Li Y B and Zhong R B 2009 *Phys. Rev.* E **80** 036602

[9] Li D and Imasaki K 2008 *J. TST* **1** 221

[10] Zhang Y X, Qiao S, Huang W X, Ling W and Li L 2011 *Appl. Phys. Lett.* **99** 073111

[11] Fu Z P, Lin F and Zhu X 2011 *Acta Phys. Sin.* **60** 114213 (in Chinese)

[12] Hu M, Zhang Y X, Yan Y, Zhong R B and Liu S G 2009 *Chin. Phys.* B **18** 3877

[13] Johnson P B and Christy R W 1972 *Phys. Rev.* B **6** 4370

[14] Simpei T, Koji I and Eiichi S 2007 *Opt. Express* **24** 16222

[15] Hessel A 1964 *Canadian J. Phys.* **42** 1195

[16] Urata J, Goldstein M, Kimmitt M F, Naumov A, Platt C and Walsh J E 1998 *Phys. Rev. Lett.* **80** 516

[17] Donohue J T and Gardelle J 2005 *Phys. Rev. ST Accel. Beams* **8** 060702

[18] Li D, Yang Z, Imasaki K and Park G S 2006 *Phys. Rev. Special Topics* **9** 040701