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Effect of plasmonic near field on the emittance of plasmon-enhanced photocathode

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ABSTRACT

The surface plasmon polaritons make the emittance of the electron beam emitted from the photocathode complicated. In this article, numerical investigations are carried out to study the influence of the plasmonic near field (PNF) excited by a square hole array on the beam emittance. The characteristics of the emittance induced by PNF are studied. The coupling between the emittance caused by PNF and the original intrinsic emittance due to the excess energy of electrons and the surface roughness of the cathode is discussed. The results provide insights into the suppression of the emittance caused by PNF and new possibilities to break the limits of the nature of the materials, improving the performance of a photocathode.

1. Introduction

With the virtue of prompt response (ps-fs), high brightness, and low emittance etc., the photocathode has become a significant enabling technology for the 4th generation light source and advanced accelerator and electron microscopy technology, such as X-ray free electron laser, inverse Compton scattering sources, energy recovery linac, and dynamic transmission electron microscopy etc. [1–3]. The metal photocathode has been studied for a long time and used in many facilities due to its high brightness, long lifetime, and low cost. On the other hand, it holds great promise to generate the electron bunch of uniform 3 dimensional ellipsoidal distribution with only linear internal space charge fields because of its ultrafast response characteristic, which is an ideal distribution for a high-brightness FEL operation [4–6]. However, because of its low quantum efficiency (QE) and high work function (∼4.6 eV@Cu), the metal photocathode usually needs to be pumped by high power ultraviolet laser which certainly increases the demand and cost for the drive laser [7].

In recent years, the plasmon-enhanced photocathode (PEP) attracts more attention, which introduces the surface plasmon polaritons (SPPs) to enhance the interaction between laser and materials [8]. With the help of the SPPs, this kind of photocathode has the potential to yield much more electrons than the traditional metal photocathode while possessing its merits of long lifetime, low vacuum requirement, prompt response, etc. [9–11], and it can operate with longer wavelength laser, reducing the demand of drive laser system [7,12].

When the surface plasmon polaritons (SPPs) are excited, the plasmonic near field (PNF), an enhanced electromagnetic field, will be formed on the air/vacuum side of the interface due to the bound surface plasmon polariton wave and decay exponentially perpendicular to the interface [13–15]. Every electron emitted from this kind of cathode has to traverse this region, which may have impact on the transverse momentum of electrons degrading the quality of the beam. In this paper, we estimate the influence of the PNF on the electron beam dynamics, explore the characteristics of the emittance caused by PNF and the coupling with the original intrinsic emittance.

2. Characteristics of the plasmonic near field

In fact, surface plasmon polarizations can be excited by a variety of sub-wavelength array structures. In this paper, a periodic square hole array is used to excite the SPPs on the surface of the photocathode and investigate its influence on the quality of the beam. Fig. 1 presents the structural diagram of the nano square hole array which is made of Au. Its geometrical parameters are shown as following, $a = b = 240$ nm, $h = 300$ nm, $p = 755$ nm. Fig. 2 shows the simulation results of the reflectivity spectrum of the nano array photocathode. In the simulation, the incident light is irradiated on the surface of the PEP perpendicularly, the electric field component is aligned with the x axis. It can be found that an abnormally enhanced absorption close to 90% occurs with the incident laser wavelength of 800 nm, which illustrates that the SPPs are excited successfully.

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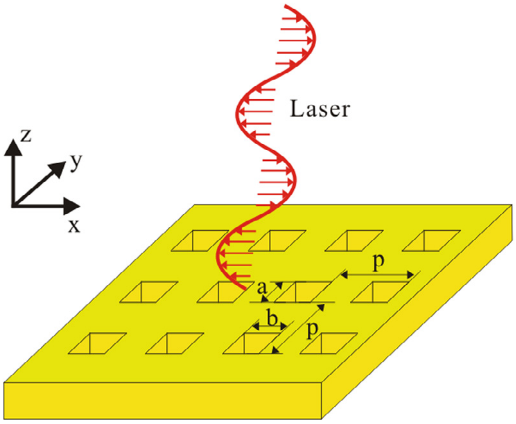

Fig. 1. The structural diagram of the nano-array used to excite the SPPs.

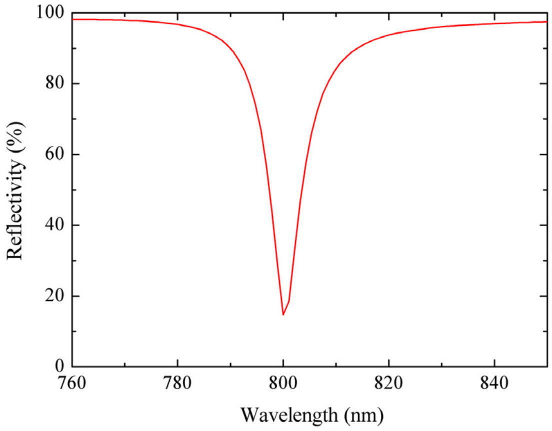

Fig. 2. The simulated reflectivity spectrum of the nano-array photocathode. The abnormal absorption occurs at the wavelength of 800 nm.

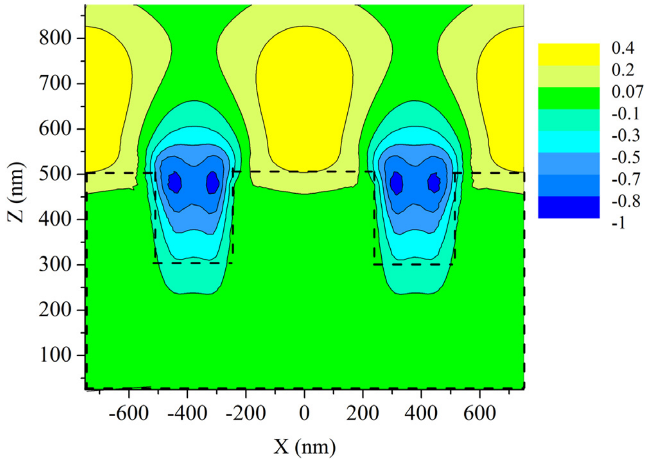

Fig. 3. The electric field distribution of the X component of the plasmonic near field at the cross section of the square hole. The dash line shows the outline of the two square holes of the array.

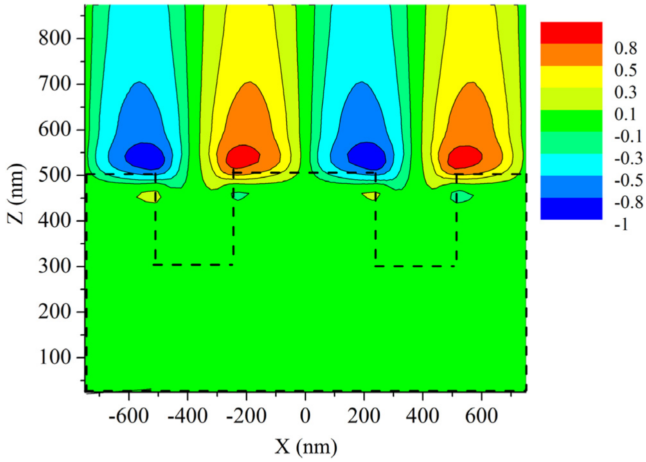

Fig. 4. The electric field distribution of the Z component of the plasmonic near field at the cross section of the square hole. The dash line shows the outline of the two square holes of the array.

With the excitation of SPPs, the electromagnetic field near the interface will be redistributed, and an enhanced plasmonic near field (PNF) will appear. As the electric field component of the incident laser is aligned with the x axis, the plasmonic near field hardly contains the electric field component of Y. Figs. 3 and 4 show the simulation results of the PNF distribution of the other two components (X and Z) of two unit cells of the square hole array at a certain phase. The dash lines give the outline of the two unit cells of the square hole. The color contour shows the normalized electric field strength, which shows that the electric field is obviously enhanced in the vicinity of interface and then decays exponentially perpendicular to it. The PNF presents periodic distribution, aligning with the square hole array, and the electric-fields of two adjacent domains are opposite. These features of the PNF will determine the specific effects on the beam dynamics in this region. As the characteristics of the PNF are related with the nano-structure array, the triggering laser and the material of the cathode, all of these hold us the possibility to depress the degrading effect of the beam quality and modulate it.

3. Emittance growth induced by the plasmonic near field

In order to demonstrate whether the surface polarization field of the plasmon can influence the emittance of the bunch, the dynamics of the beam in the PNF region are simulated by the CST STUDIO. In the simulation, the RF module gives the results of the PNF, and the Particle module is used to simulate the beam dynamics with the PNF. Due to the periodic feature of the PNF, the model of the cathode used in the simulations to excite the SPPs and emit electrons is a 5 × 5 square hole array. Its geometrical sizes and material are the same as shown above, so the PNF distribution is similar with that presented in Figs. 3 and 4. In order to explore the effect of the PNF on the beam dynamics, eliminating distractions from other factors, it is assumed that the electrons are emitted from the entire surface uniformly without any initial energy. The electrons emitted from the cathode are accelerated by a biased electric field of 10 MV/m and then collected by the anode.

When the SPPs are not excited, the transverse phase-space distributions of the bunch projected at X and Y directions are presented in Fig. 5 (a) and (b), which can be used as the reference compared with those with the SPPs. The spikes in the transverse phase-space result from the distorted static electric field caused by the symmetrical square holes. Fig. 5 (c) and (d) respectively present the transverse phase-space distributions of the bunch projected at X and Y directions when the SPPs are excited. Fig. 5 (d) and (b) illustrate that the plasmonic near field has little effect on the transverse phase-space of the bunch projected at Y direction. But the transverse phase-space projected at X direction shown in Fig. 5 (c) presents obviously cyclical fluctuations, aligning with the square hole array of the cathode, which is different with Fig. 5 (a) and (d). Because of its symmetry feature of the structure and the linear polarization triggering laser, the transverse phase-spaces