# PRIMARY STUDY OF THE PHOTOCATHODE ELECTRON GUN WITH A CONE CATHODE AND RADIAL POLARIZATION LASER *

R. Huang †, Qi-ka. Jia‡
NSRL, University of Science and Technology of China, Hefei, Anhui, 230029, China

*Abstract*

The linearly polarized laser with oblique incidence can achieve a higher quantum efficiency (QE) of metal cathodes than that with the normal incidence, which however requires the wavefront shaping for better performance. To maintain the high QE and simplify the system, we propose a cone cathode electron gun with a radial polarization laser at normal incidence. The primary analytical estimation and numerical simulations are explored for its effect on the emittance of the electron beam.

## INTRODUCTION

High-brightness electron beam, which can be used for the 4th generation light sources such as X-ray free electron lasers [1], requires the high current and low emittance. In photocathode electron guns, a metal cathode is widely used to emit electrons for its long lifetime. One of the major limitation is the low quantum efficiency(QE), especially for guns with the metal cathodes [2]. It was found that the QE had a significant dependence on the incidence angle and polarization state when the laser illuminated the cathode [3,4]. Early work on Cu showed that the p-polarized laser at 60-70° off normal incidence would give a QE at 5-14 times the normal incidence yield [5]. The primary cause of the QE enhancement is that a surface photoemission is stimulated by the normal electric field of the p-polarized laser with oblique incidence.

The scenario of oblique incidence would result in an ellipsoidal spot on the cathode and a pulse delay in laser wavefront. Thus spatial and temporal laser shaping [6] is required to prevent the distortion of the emitted beam and to improve the initial beam quality. The shaping technique is still challenging and makes the system more complicated and expensive. Some devices still take the normal incidence scheme, which would simplify the system but sacrifice some QE.

To maintain the high QE and also simplify the system, we propose a cone cathode electron gun with a radial polarization laser at normal incidence.

## THE PROPOSED SCHEMES

There are two possible schemes of the cone cathode, as shown in Fig. 1. When the laser illuminates a cone cathode at normal incidence, the local incidence angle is an oblique one. The cone is properly designed so that the angle $\theta$ equals the optimized oblique angle on a flat cathode which gives a maximum QE. For the photogun in University of Science and Technology of China (USTC) [7], $\theta$ is about 67°.

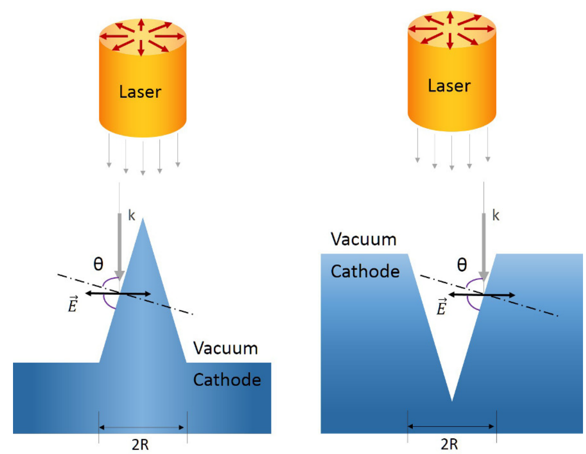


Figure 1: Normal incidence on the cathode like a conical roof (left) and the cathode like a conical sink (right).

The left plot of Fig. 1 shows the normal incidence scheme on a cathode like a conical roof, while the right one shows the scheme on a cathode like a conical sink. In stead of linearly polarized laser on a flat cathode, a radial polarized laser [8] is required for the case of a cone cathode. $k$ is the wavenumber of the incidence laser. $\overrightarrow{E}$ is the electric field component of the laser, with an angle $\theta$ to the local cathode surface. The radius of circular cone $R$ equals the rms spot size of the laser.

This scheme could enhance the QE as well as achieve a circular laser spot on the cathode. It is also notable that the pulse delay in the proposed scheme is only half the case of the oblique incidence. The cone cathode may also encounter some issues. The uneven cathode surface may bring about a growth in the thermal emittance. Besides, the cone geometry of the cathode could change the field distribution in the gun cavity, which would further influence the beam dynamics.

In the following, we will firstly build a model to analytically evaluate the emittance growth introduced by a cone cathode. Secondly the RF gun design will be studied to analysis the field distribution in the cavity. Finally we will give a primary study on the beam dynamics in the gun.

## THE EMITTANCE GROWTH

The thermal emittance for the photoelectric emission in a metal cathode is derived from the Fermi-Dirac model [9]. The dimensionless transverse momentum was found to be

$$\sigma_{p_x} = \sqrt{\frac{h\nu - \phi_{\text{eff}}}{3mc^2}}, \tag{1}$$

* This work is partly supported by the National Nature Science Foundation of China under Grant No. 11375199.
† hruixuan@mail.ustc.edu.cn
‡ jiaqk@ustc.edu.cn

the normalized emittance was obtained by $\varepsilon_n = \sigma_x \sigma_{p_x}$.

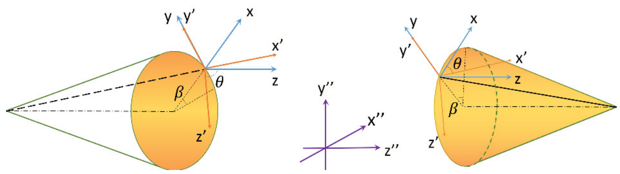

Figure 2: The sketchs for the cathodes like a conical roof (left) and a conical sink (right): the local coordinates (red), the 2D surface coordinates (blue), the 3D global coordinates (purple), with the related rotation angles $\theta$ and $\beta$.

Based on the bulk emission model, we make the model of the cone cathode with the coordinates configuration in Fig. 2. Where the $C'(x', y', z')$ is the local coordinate, and the laser is at oblique incidence with an angle equal $\theta$. The $C(x, y, z)$ is the 2D surface coordinate which is transferred from $C'$ by applying the rotation matrix

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{pmatrix} \begin{pmatrix} x' \\ y' \\ z' \end{pmatrix}. \tag{2}$$

This gives an expression for the particle momentum in the 2D surface coordinate:

$$p_x = p'_x \cos\theta - p'_z \sin\theta, \quad p_y = p'_y. \tag{3}$$

In local system, the particle momentum from a sloped surface [10] is given in the form

$$p'_x = \sqrt{2m(E + h\nu)} \sin\Psi' \cos\Phi', \tag{4}$$

$$p'_y = \sqrt{2m(E + h\nu)} \sin\Psi' \sin\Phi', \tag{5}$$

$$p'_z = \sqrt{2m(E + h\nu)\cos^2\Psi' - 2m(E_F + \phi_{\text{eff}})}. \tag{6}$$

If an electron in the material absorbs the laser energy, it could go towards the surface with a direction angle ($\Psi'$, $\Phi'$) and finally escape from the surface. $E$ is the electron energy, $E_F$ is the Fermi level, $h\nu$ is the photo energy, $\phi_{\text{eff}}$ is the effective work function. One can obtain the momentum expression in the 2D surface coordinate by substituting Eq. (4) into Eq. (3).

By further rotated in angle $\beta$, the 2D surface coordinate becomes the global coordinate $C''(x'', y'', z'')$:

$$\begin{pmatrix} x'' \\ y'' \\ z'' \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta & 0 \\ \sin\beta & \cos\beta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix}. \tag{7}$$

The particle momentum in the global coordinate is given by

$$p''_x = p_x \cos\beta - p_y \sin\beta, \quad p''_y = p_x \sin\beta + p_y \cos\beta. \tag{8}$$

The variance of the transverse momentum can be calculated from the three-step model of the photoemission [9]. Note that the $\beta$ angular integrations can be done separately. The variance of the transverse momentum results in

$$\sigma^2_{p''_x} = \frac{\int_{E_m}^{E_M} d\mathbb{E} \int_{\cos\Psi_{\max}}^{1} d(\cos\Psi) \int_0^{2\pi} d\Phi p_x^2}{(mc)^2 \int_{E_m}^{E_M} d\mathbb{E} \int_{\cos\Psi_{\max}}^{1} d(\cos\Psi) \int_0^{2\pi} d\Phi}, \tag{9}$$

where $E_M = E_F + h\nu$, $E_m = E_F + \phi_{\text{eff}}$, $\mathbb{E} = E + h\nu$, $\cos\Psi_{\max}$ is $\sqrt{E_m/E_M}$.

After some algebra, the variance of $p_x$ has the form of:

$$\sigma^2_{p_x} = \frac{1}{3mc^2}\left(E_M^{\frac{1}{2}} - E_m^{\frac{1}{2}}\right)\left(E_M^{\frac{1}{2}} + E_m^{\frac{1}{2}} + 2\sin^2\theta E_m^{\frac{1}{2}}\right) \tag{10}$$

Substituting Eq. (10) into Eq. (9), one could obtain that

$$\sigma^2_{p''_x} = \frac{1}{2}\left(\sigma^2_{p_x} + \sigma^2_{p_y}\right). \tag{11}$$

In Eq. (11), the first and second terms denote the variance of the horizontal and vertical momentums in the 2D surface coordinate, respectively. From Eq. (3), we see that $p_y$ is independent of $\theta$. Therefore, the emittance from a cone cathode is the average value of the emittance from a flat cathode and from a sloped cathode, which turns out to be

$$\varepsilon''_n = \sigma_x \sqrt{\frac{\left(E_M^{\frac{1}{2}} - E_m^{\frac{1}{2}}\right)\left(E_M^{\frac{1}{2}} + E_m^{\frac{1}{2}} + \sin^2\theta E_m^{\frac{1}{2}}\right)}{3mc^2}}. \tag{12}$$

If we compared Eq. (12) with Eq. (1), and defined an emittance growth factor $\xi = \varepsilon''_n/\varepsilon_n$, $\xi$ could be written as

$$\xi = \sqrt{1 + \frac{\sin^2\theta}{1/\cos\Psi_{\max} + 1}}. \tag{13}$$

$\xi$ is in the range of 1 to about 1.225, which means the emittance from a cone cathode is always larger than the emittance from a flat cathode. For our photogun with $\theta$ of 67°, the theoretical emittance growth is 19.2%.

## RF FIELD DISTRIBUTION

The field solver SUPERFISH [11] was used to design the RF gun with a cone cathode. The gun operates in the $\pi$ mode with $f$=2.856 GHz.

For the cathode like a conical sink, the gun geometry along with the RF field is shown in Fig. 3. The geometry is a typical 1.6-cell gun except for minor difference at the cathode. The radial component of this field forms an RF focusing near the cathode, while the longitudinal component is weakened. Although the RF focusing may expect an decrease in transverse beam size and emittance, the puny accelerating field is detrimental to the electrons emission. Overall, the conical sink design of the cathode is not suitable for the normal incidence scheme.

With a cathode like a conical roof, the field is shown in Fig. 4. The longitudinal electric field on the cathode is large enough to overcome the potential barrier and emit electrons. The beam will see a defocuing force in the radial direction, thus a solenoid is necessary to provide a sufficient focusing.

Simulation shows that $E_z$ is gradually increased along $z$ at the region of conical roof and reaches the peak value at the tip. The sharp tip may greatly enhance the local field and cause field-emitted electrons which is also called dark current emission. In order to maintain a high nominal accelerating field and to reduce the dark current, the geometry of the conical cathode should be further optimized.

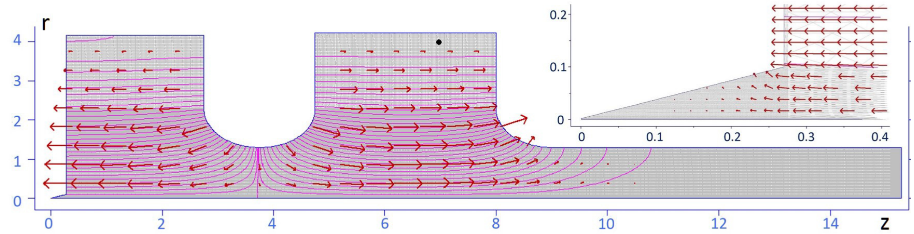

Figure 3: The field distribution in the gun cavity with a conical sink cathode. The insert is a zoom-in of the cathode area.

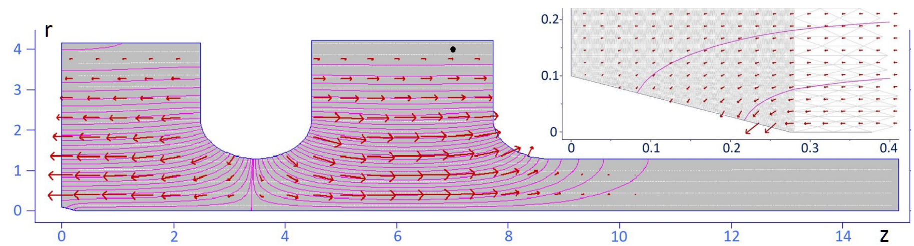

Figure 4: The field distribution in the gun cavity with a conical roof cathode. The insert is a zoom-in of the cathode area.

## BEAM DYNAMICS SIMULATION

Due to the complexity in the geometry and distortion of the field distribution, the beam dynamics simulation in the gun with a conical cathode is not straightforward. The common simulation codes can't build such model directy.

In our simulation configuration, the beam dynamics study is performed in two steps with ASTRA code [12]. In this paper, only the cathode like a conical roof is considered. First, we will build a circlet beam on the cathode and track the particles in the RF gun. Then, we longitudinally superpose several circlet beams with different radii and set up a practical beam from a cone cathode.

Totally 10 slices with different numbers of macroparticles in each circlet slice are assumed. As a result, the overal particle distribution is roughly uniform. The initial pulse length is neglected at present. In Fig. 5, the left plots have shown the transverse and longitudinal beam distribution at the cathode, while the right plots have shown the distribution at the gun exit. Compared with the initial beam, the beam at gun exit has a significant increase in transverse size and has an elongation in longitudinal size (like a bow). The beam elongation is due to the varied longitudinal field, where the local fields are enhanced by the presence of sharp tip.

Simulation indicates that the field distortion induced by the cone cathode has a major effect on the beam size, while a minor effect on the beam emittance. The most emittance growth comes from the geometry of the cone cathode.

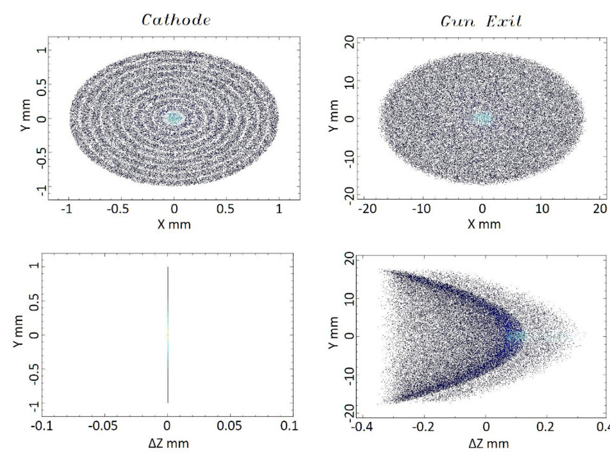


Figure 5: Transverse (upper) and longitudinal (bottom) distribution at the cathode (left) and gun exit (right), respectively.

## SUMMARY

The photocathode electron gun with a cone cathode and radial polarization laser at normal incidence was proposed to maintain the high QE of metal cathodes. Compared with the case of oblique incidence, the new scheme could achieve a circular beam spot and only has a half pulse delay of the obllique incidence. Analytical model of the cone cathode was built to evaluate the transverse emittance of the emitted beam. For a typical $\theta$ of 67°, the emittance growth is about 19%. Based on the computation of the RF field in the gun, the primary research of the beam dynamics was given by a two-step simulation. A cathode like a conical roof would be a potential scheme. More accurate simulation and optimization will be investigated. beam dynamics study should be investigated, by considering the field effect and with a more accurate simulation model.

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