FIRST PRINCIPLE MEASUREMENTS OF THERMAL EMITTANCE FOR COPPER AND MAGNESIUM

Dao Xiang[#], Wen-Hui Huang, Ying-Chao Du, Li-Xin Yan, Ren-Kai Li, Chuan-Xiang Tang, Yu-Zheng Lin, Department of Engineering Physics, Tsinghua University, Beijing, China
Sung-Ju Park, Pohang Accelerator Laboratory, POSTECH, Pohang, South Korea
Jangho Park, ATF, Brookhaven National Laboratory, Upton, NY, 11973, USA

Abstract

There are growing interests in generation, preservation and applications of high brightness electron beam. With the rapid development in the techniques for emittance compensation, laser shaping and generation of ellipsoidal beam, we are approaching the limit--the uncorrelated thermal emittance. In this paper, we describe the design of the angle-resolved photoemission spectroscopy for measurements of thermal emittance for Cu and Mg. The measurement is conducted in a field-free region. The energy spectrum and angular distribution of the electrons will be measured immediately after its emission and further used to reconstruct the initial phase space and the corresponding thermal emittance. We also show how cathode surface roughness and laser incidence angle as well as its polarization state affect the quantum efficiency and thermal emittance.

INTRODUCTIONS

High charge low emittance electron beam is crucial for the X-ray free electron lasers (XFEL) and Thomson Scattering based X-ray source (TSXS). it is conventionally provided by photocathode RF gun where the beam is generated by UV laser illuminating the cathode and then rapidly accelerated to relativistic to reduce emittance growth due to space charge as occurred in thermionic RF gun and DC gun. The most effective way to reduce the cost of an XFEL facility and increase the X-ray yield of a TSXS may be to produce low emittance and high-peak current electron beam. Thus high quantum efficiency (QE) and low thermal emittance are the key figure of merit for a good photocathode candidate.

Generally speaking, the total transverse emittance has three contributions: linear and nonlinear RF force, linear and nonlinear space charge force and thermal emittance [1]. With the rapid development in the techniques for emittance compensation [2-3], laser shaping [4] and generation of ellipsoidal beam [5], the emittance due to RF force and space charge force can be largely suppressed, thus the limit of the emittance achievable is ultimately the uncorrelated thermal emittance which can be defined as follows,

$$\varepsilon_n = \frac{1}{m_0 c}\sqrt{\left\langle x^2\right\rangle\left\langle p_x{}^2\right\rangle - \left\langle x p_x\right\rangle^2}\ , \qquad (1)$$

It is justified to assume that there is no correlation between momentum and position, so the thermal emittance can be simplified to,

$$\varepsilon_n = \sigma_x\sqrt{\frac{\left\langle E_{kin}\sin^2\theta\right\rangle}{m_0 c^2}}\ , \qquad (2)$$

where σ_x is the root mean square (rms) beam size in horizontal direction, θ is the angle measured with respect to the cathode surface normal and E_{kin} is the kinetic energy of the electron. Conventionally it has been assumed that the angular distribution of the emitted electrons is isotropic, so Eq.(2) can be rewritten as,

$$\varepsilon_n = \sigma_x\sqrt{\frac{\left\langle E_{kin}\right\rangle}{2 m_0 c^2}}\ , \qquad (3)$$

Based on Eq.(3), most of the endeavors have been devoted to decreasing the kinetic energy of the electrons: by properly choosing cathode material whose work function is close to the energy of the laser photons, by utilizing Schottky effect [6] and using negative electron affinity semi-conductors [7], etc. In our previous work [8], we have argued that the thermal emittance and QE was dependent on polarization state and incidence angle of the UV laser. In this paper we will briefly review the theory and present the design considerations of the equipments for experimental demonstration. The surface roughness induced emittance growth is also discussed.

THEORIES ON MANIPULATING THERMAL EMITTANCE AND QE

It has been reported by several groups that the QE is 4-6 times higher for p-polarized laser than that for s-polarized case at some specific oblique incidence angles [9-10]. This effect can be partially explained by the reflection rate difference which makes the QE for p-polarized laser 2 times higher than that for s-polarized case when the incidence angle is about 70 degrees. Another 3 times has been attributed to the Schottky effect from the laser field. A moment's reflection would contradict the explanation because the QE is independent of the laser energy while the laser field does depend on it. We have suggested a more reasonable explanation that the QE increase is caused by surface photoemission which only happens for p-polarized laser at oblique incidence [8].

Any process in which an electron absorbs one or more photons, migrate to the surface, penetrate through the surface barrier and escape into the vacuum may be called

[#] xiangdao@tsinghua.org.cn

photoemission. Since a photon carries energy but little momentum, a completely free electron cannot absorb a photon and simultaneously conserve both energy and momentum. For bulk photoemission, this conservation is fulfilled by the lattice vector and for surface photoemission the surface serves as a source of momentum. As demanded by uncertainty principle, confinement of the wave function into a few angstroms in the surface region increases the normal momentum spread to a value that may be large enough to conserve the momentum in the transition between electronic states. Surface photoemission can only be initiated by the presence of the rapid variation of the longitudinal component of the vector potential inside the cathode for which the laser should be p-polarized and illuminates the cathode at oblique incidence.

As a first approximation, we assume that the number of initial and final states is high enough that the photoemission current is only determined by the photoionization matrix element [8],

$$M_{fi} = \frac{-iA_0}{E_f - E_i}\sum_{\vec{G}} V_{\vec{G}} \exp(i\vec{G}\cdot\vec{r})\left\langle f\left|\vec{e}\cdot\vec{G}\right|i\right\rangle - \frac{-i}{E_f - E_i}\left\langle f\left|\vec{A}\cdot\nabla V_S\right|i\right\rangle - i\hbar\left\langle f\left|\frac{\partial A}{\partial z}\right|i\right\rangle,$$

where E_f is the final state energy, E_i is the initial state energy, M_{fi} is the transition matrix element between the initial and final states, $\vec{G}$ is the reciprocal lattice vector, $\vec{A}$ is the vector potential of the incident laser field, $|i\rangle$ and $|f\rangle$ are the initial and final states, $\vec{e}$ is the unit vector in the polarization direction.

When the laser is incident normally or when the s-polarized laser is at oblique incidence, the field is nearly constant in the surface region and the third term in the matrix element is zero everywhere. For a polycrystalline material which is the case for most of the cathodes used in photoinjectors, the lattice vector can be in any direction. So it is reasonable to consider the electrons to be isotropicly photoexcited and emitted. However, as for p-polarized laser at oblique incidence, the presence of the normal field results in a discontinuity of the dielectric constant at the interface and the field inside the solid changes rapidly within a few angstroms from the surface. So the divergence of the vector potential could take appreciable value, which is considered the major contributor to surface photoemission. Due to the extra contribution, the QE will be higher for p-polarized laser at oblique incidence than that for s-polarized or normal incidence case. The more important feature is that the electrons from surface photoemission are emitted more preferably in the normal direction, which results in further reduction of thermal emittance. The reason for the existence of this preferred direction is that the variation of the vector potential that plays the role of the lattice vector is only in the normal direction.

The quantum efficiency ratio of p-polarized laser at oblique incidence to that for normal incidence is calculated following [8] and shown in Fig.1.

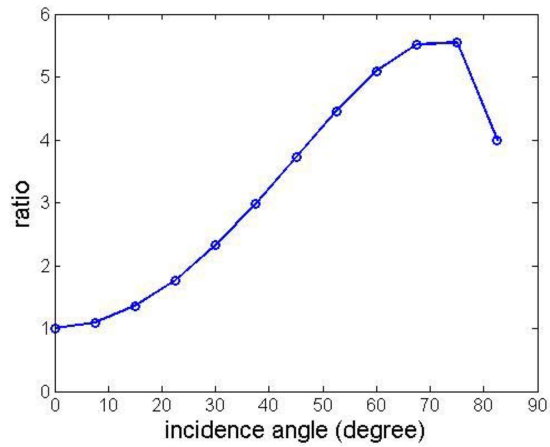

Fig.1 QE ratio of p-polarized laser at oblique incidence to that for normal incidence.

From Fig. 1 we can see that at an incidence angle of 70 degrees or so, the QE is increased by more than 5 times. Even though to correct the wave front of the laser for oblique incidence would lose a few percent of the laser energy, the higher QE makes it capable of generating more electrons than the normal incidence scheme.

The angular distribution of the electrons contributed by surface photoemission was found to follow a $\cos^2\theta$ distribution. It is safe to assume an isotropic distribution for those from bulk photoemission. After taking into account the two kinds of photoemission, the thermal emittance is given by [8],

$$\varepsilon_n = \sigma_x\sqrt{\frac{4 + Y_{ratio}(\hbar\omega)\upsilon_p(\phi)}{8(1 + Y_{ratio}(\hbar\omega)\upsilon_p(\phi))}\frac{\langle E_{kin}\rangle}{m_0c^2}}, \quad (4)$$

where $Y_{ratio}(\hbar\omega)$ is the ratio of the characteristic surface to bulk photoemission yield which is independent of the incidence angle, $\upsilon_p(\phi)$ contains all the information that is relevant to incidence angle and their product gives the real surface to bulk photoemission yield ratio. For normal incidence and s-polarized laser at oblique incidence, $\upsilon_p = 0$ and Eq.(4) reduced to Eq.(3). As for a p-polarized laser at oblique incidence, an estimation using Eq.(4) indicates a reduction of thermal emittance by nearly 40 percent at an incidence angle of 60~70 degrees as compared to that at normal incidence.

SURFACE ROUGHNESS INDUCED EMITTANCE GROWTH

Practical cathode surface inevitably has roughness. The presence of the surface roughness introduces a transverse electric field that increases the transverse energy of the electron, which finally causes emittance growth. For simplicity while not losing generality, we assume the

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shape of the rough surface to be $z = a\cos(2\pi x / b)$, where a is the amplitude of the uneven surface, b is the period of the fluctuation. Under the influence of the roughness, the electron with initial position x_0 will finally get a transverse momentum [11-12],

$$p_x = \frac{2\pi a m_e}{b}\sin(2\pi x_0 / b)\left[\frac{eE_{rf}\sin\theta_{rf} b}{4m_0}\right]^{1/2}, \quad (5)$$

Substituting Eq.(5) into Eq.(1) and performing the average we get the surface roughness induced emittance,

$$\varepsilon_{ns} = \sigma_x\sqrt{\frac{e\pi^2 a^2 E_{rf}\sin\theta_{rf}}{2m_0 c^2 b}}, \quad (6)$$

To see how much this contributes to total normalized emittance, we consider the typical parameters: $E_{rf} = 100$ MV/m, $\theta_{rf} = 30^0$, $\sigma_x = 0.5$ mm, and $a = 70$ nm, $b = 3\mu m$ from the light interference measurement results for our cathode; the surface induced emittance is found to be about 0.44 $mm \cdot mrad$. it's worth pointing out that this term increases as field gradient increases, so it could be a limiting factor when operating the photocathode rf gun in very high field gradient.

DESIGN OF THE ANGLE-RESOLVED PHOTOEMISSION SPECTROSCOPY

Considering the cathode surface roughness, measurement of thermal emittance in a field free condition is quite desirable in order to give unambiguous results. Using the angle-resolved spectroscopy to measure thermal emittance for Ag and Cs2Te has been implemented in [13] where the laser illuminates the cathode with normal incidence. To study the thermal emittance for oblique incidence case, a special spectroscopy is designed. The layout of the angle-resolved photoemission spectroscopy is shown in Fig.2.

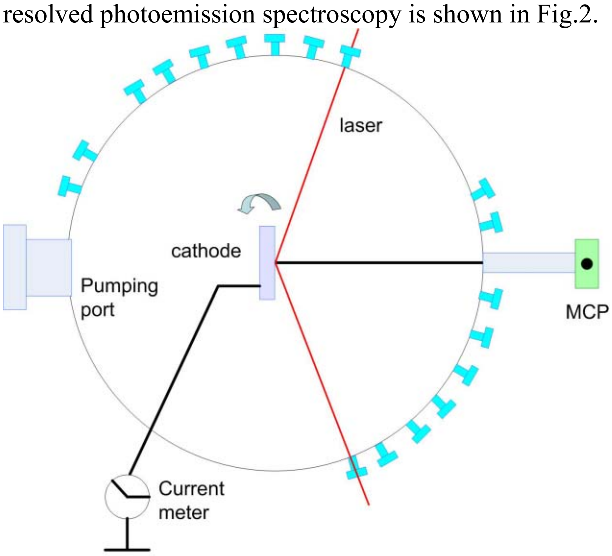

Fig. 2 Layout of the spectroscopy

The cathode can be rotated to keep the incidence angle to be 70 degrees. 18 laser ports (9 for laser in and 9 for laser out) are used to provide 10 degrees resolution for the angular distribution measurement. The electron is measured with a MCP (Hamamatsu, F9892-11) detector. The energy resolution is limited by the impulse response of the MCP which is about 2 ns corresponding to 4 meV energy resolution when the photoelectron energy is 1 eV. After the energy spectrum and angular distribution of the photoelectrons are measured, the thermal emittance can be reconstructed. As the MCP has single electron detection capability, to avoid the space charge effect, the electron number per pulse will be controlled to less than 2000. The laser energy for generating this beam is only a few tens of pJ, which is far smaller than that used in photoinjector. The use of such low intensity laser will effectively avoid two-photon photoemission that potentially increases the kinetic energy of the emitted electron and may result in large thermal emittance.

The earth magnetic field in Beijing is about 50 uT. For an electron with 1 eV energy, the Larmor radius is about 4 cm. To make the photoelectron flies from the cathode to MCP detector in a straight trajectory, the chamber is shielded with permalloy. We also plan to use a series of coils to further compensate the residual magnetic field which is expected to be less than 0.5 uT.

The spectroscopy is in fabrication and we plan to perform the thermal emittance experiment for Cu and Mg in September this year.

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REFERENCES

[1] B.E. Carlsten, Nucl. Instr. and Meth. in Phys. Res.A, 285 (1989) 313.
[2] X. Qiu, *et al*, Phys Rev Lett, 76 (1996) 3723.
[3] Luca. Serafani and James.B. Rosenzweig, Phys Rev E 55 (1997) 7565.
[4] C. Limborg-Deprey and P.R. Bolton, Nucl. Instr. and Meth. in Phys. Res.A, 557 (2006) 106.
[5] O.J. Luiten, *et al*, Phys Rev Lett, 93 (2004) 094802.
[6] Zikri M. Yusof, Manoel E. Conde, and Wei Gai, Phys Rev Lett, 93 (2004) 114801.
[7] J.E. Clendenin, *et al*, Nucl. Instr. and Meth. in Phys. Res.A, 455 (2000) 198.
[8] Dao Xiang *et al*, Nucl. Instr. and Meth. in Phys. Res.A, 562 (2006) 48.
[9] T. Srinivasan-Rao, *et al*, Rev. of Sci. Instr, 69 (1998) 2292.
[10] D.A. Reis, Ph.D. Thesis, Univ. Rochester, June 1999, UR-1573.
[11] D.J. Bradley *et al*,, J. Phys. D, 10 (1977) 111.
[12] X.Z. He *et al*, High Energy Physics and Nuclear Physics, 28 (2004) 1007, in Chinese.
[13] Daniele Sertore, *et al*, EPAC04, p408.

