EXPERIMENTAL INVESTIGATION OF PHOTOCATHODE THERMAL EMITTANCE COMPONENTS WITH A COPPER CATHODE*

H. J. Qian#, C. Li, Y. C. Du, L. X. Yan, J. F. Hua, W. H. Huang, C. X. Tang,
Department of Engineering Physics, Tsinghua University, Beijing 100084, China

Abstract

With progress of photocathode RF gun technology, thermal emittance has become one of the primary limitations of electron beam brightness [1]. Extensive efforts have been devoted to study thermal emittance, but experiment results diverge between research groups and few can be well interpreted [2]. In this paper, we report an experiment of characterizing online photocathode work function, field enhancement factor and surface roughness effect by measuring electric field dependence of photoemission quantum efficiency (QE) and thermal emittance in a Cu-cathode RF gun. Preliminary experiment results reveal huge thermal emittance contributed by surface roughness for the first time, and are in reasonable consistency with theoretical model prediction [3].

INTRODUCTION

Photoinjector technology has witnessed enormous improvements during the last decade [4] and its sensational beam brightness has enabled the success of the first hard X-ray free electron laser (LCLS) [5]. To make XFEL more compact and efficient, the photoinjector beam brightness need further upgrade, and the limitations rely on the RF gun acceleration gradient and thermal emittance [1]. Acceleration gradient is boosted by moving to higher frequencies, such as X-band and C-band [6, 7], and a gradient of 200 MV/m has been realized in an X-band RF gun [6], which is expected to deliver an electron beam with beam brightness a factor of ~5 higher than that from LCLS photoinjector [8]. Thermal emittance depends on a lot of factors, and first of all the photoemission type, surface photoemission or volume photoemission. Surface photoemission induced by p polarized laser or Surface Plasmon is expected to enhance the cathode QE and meanwhile keep a small thermal emittance [9-11], which is ideal for photoinjector cathode, but few experiment studies are conducted in this field. Volume photoemission cathode, as the current workhorse of photoinjectors, is extensively studied [2, 12]. Volume photoemission thermal emittance depends on photon energy, cathode work function, Schottky effect and surface roughness, and it has been proposed to minimize the thermal emittance by matching the photon energy with the effective work function [13-14] at the sacrifice of QE. Experiment studies of volume photoemission are rich but diverge between research groups and few can be well interpreted [2], even for the most commonly used copper cathode [15-16]. One possibility is the undefined online cathode surface conditions, which may cause difference of work function, field enhancement factor and surface roughness, and lead to thermal emittance variations.

In this paper, we report an experiment of measuring electric field dependence of QE and thermal emittance of a Cu-cathode. By fitting data to QE model and thermal emittance model, online photocathode work function, field enhancement factor and surface roughness effect can was extracted, and reveals huge thermal emittance contributed by surface roughness. First the experiment setup is introduced, and then the models of QE and thermal emittance to fit the experiment data are explained. Finally, preliminary experiment results are discussed.

EXPERIMENT SETUP

Tsinghua University has been developing Compton scattering X-ray sources, and a ~45 MeV photoinjector beamline was built, which consists of a BNL type S-band RF gun, a SLAC type 3 meter travelling linac and a TW Ti:Sapphire laser [17]. This experiment was done at the front end of the Compton scattering beamline (see Fig. 1), electron beam is generated by near normal incident UV laser (266 nm), and accelerated to ~1.8 MeV in the gun with gradient of 40 MV/m. Beam charge is measured with a Faraday cup, and emittance is measured by solenoid scan technique [18-19], which consists of the combination of the gun solenoid and a YAG screen (100 μm thick) 105 mm from the cathode. The beam profile is measured with a very sensitive Andor EMCCD camera due to an ultralow charge (~0.1 pC) used in thermal emittance measurement.

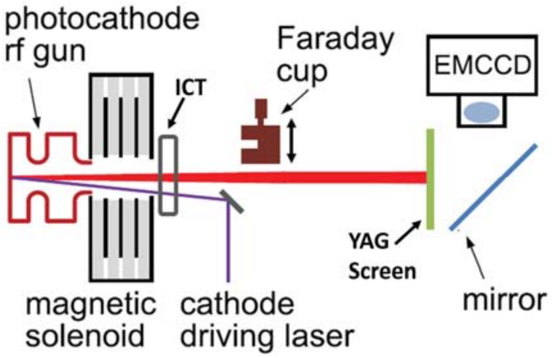

Figure 1: Experiment setup at Tsinghua Compton scattering beamline.

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#qhj@mails.thu.edu.cn

MODEL OF QE AND THERMAL EMITTANCE

The QE of a photocathode near the photoemission threshold can generally be expressed in the following form [12]:

$$QE = a(\hbar\omega - \phi_w + \sqrt{\frac{e\beta E}{4\pi\varepsilon_0}})^2 = a(p_1 + p_2\sqrt{E})^2 \quad (1)$$

Where $\hbar\omega$ is the photon energy, ϕ_w is the cathode work function, β is the field enhancement factor, E is the electric field at photoemission, a is a constant when E varies in a small range, $p_1 = \hbar\omega - \phi_w$ and $p_2 = \sqrt{\frac{e\beta}{4\pi\varepsilon_0}}$.

By linear fitting $\sqrt{QE}$ versus $\sqrt{E}$, we got the ratio of p_1/p_2, and the gap between the photon energy and the work function can be evaluated by Eq. (2), which gives a good evaluation of the cathode online work function.

$$\begin{aligned}\hbar\omega - \phi_w &= (p_1/p_2)\sqrt{e\beta/(4\pi\varepsilon_0)} \\ &\geq (p_1/p_2)\sqrt{e/(4\pi\varepsilon_0)}\end{aligned} \quad (2)$$

For an ideal flat metal cathode, the thermal emittance is formulated in Eq. (3) within the 3-step model [12].

$$\frac{\varepsilon_{thermal}}{\sigma_{laser}} = \sqrt{\frac{\hbar\omega - \phi_w + \sqrt{e\beta E/(4\pi\varepsilon_0)}}{3mc^2}} \quad (3)$$

Practical cathode has surface roughness, which induces transverse electric field in the immediate vicinity of the cathode surface. The transverse electric field gives rise to transverse momentum of the electron beam, and leads to thermal emittance growth. A previous theoretical study based on an ideal 1D roughness model shows roughness induced emittance is square root dependent on electric field (see Eq. (4)) [3].

$$\frac{\varepsilon_{roughness}}{\sigma_{laser}} = \sqrt{\frac{e\pi^2 a_n^2 E}{2mc^2\lambda_n}} \quad (4)$$

Where a_n is the roughness amplitude, λ_n is the roughness period, E is the electric field.

The thermal emittance caused by photoexcitation (Eq. (3)) and roughness effect (Eq. (4)) are assumed to be uncorrelated, so the total thermal emittance is,

$$\begin{aligned}\frac{\varepsilon^{total}_{thermal}}{\sigma_{laser}} &= \sqrt{\varepsilon^2_{thermal} + \varepsilon^2_{roughness}} \\ &= \sqrt{\frac{p_1 + p_2\sqrt{E} + p_3 E}{3mc^2}}\end{aligned} \quad (5)$$

Where $p_3 = 3e\pi^2 a_n^2/(2\lambda_n)$.

According to equation (5), the square of thermal emittance versus the square root of electric field is a parabola, and least square fitting will extract value of work function, field enhancement factor and roughness emittance. Since p_2 and p_3 are positive value, the fitting is at one side of the parabolic bottom, thus very sensitive to emittance measurement error. If we put the QE fitting (Eq. (1)) result, i.e. the value of p_1/p_2, into emittance model fitting, then,

$$\frac{\varepsilon^{total}_{thermal}}{\sigma_{laser}} = \sqrt{\frac{\sqrt{\beta}(\frac{p_1}{p_2} + \sqrt{E})\sqrt{\frac{e}{4\pi\varepsilon_0}} + p_3 E}{3mc^2}} \quad (6)$$

The emittance model fitting will have only two unknown numbers, which are the field enhancement factor and coefficient of the surface roughness item, and more importantly is also much less sensitive to emittance measurement error.

PRELIMINARY EXPERIMENT RESULTS

The experiment was conducted in May and August of 2011, in between an accident happened in which a newly installed part contaminated the vacuum of the RF gun, and change of cathode status was observed during QE and thermal emittance measurement. In order to avoid the inconsistency of emittance and QE data between the two rounds of experiments, we decided to redo the whole experiment after cathode contamination, but only part of the experiment was finished.

QE Measurement

In the first round experiment, QE versus electric field was not measured, but we found a QE record ($4.6\text{x}10^{-5}$) in June's operations. QE was measured at 35 deg with a gun gradient of 65 MV/m, and UV laser was ~5 ps (FWHM). After cathode contamination, the RF gun gradient is set at 40 MV/m, and QE was measured at different laser-RF phases. The QE data and model fitting to Eq. (1) is shown in Fig. 2.

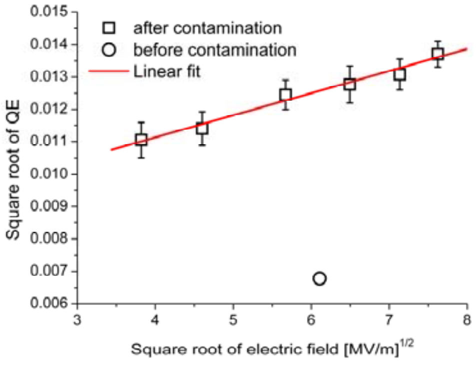

Figure 2: QE data and model fitting.

Surprisingly, the copper cathode QE rise by a factor of ~3.5 to the 10^{-4} after contamination, which is close to the highest QE reported at this wavelength for Cu cathode [20]. The QE change is not understood at this moment, and we plan to do offline analysis when the gun is retired in the coming October. The fitting of the QE data shows p_1/p_2 is 12.2±1.3 $(\text{MV/m})^{1/2}$, and this means the lower limit of the difference between photon energy and work function is 0.46±1.3 eV.

Thermal Emittance Measurement

To measure the thermal emittance with solenoid scan, the space charge effect and RF effect have to be reduced, so an ultrashort (~100 *fs*) laser pulse with energy to generate ~0.1 pC charge was normally incident on the cathode. Our RF gun has a high dark current level, so the gun gradient was lowered to 40 MV/m to reduce background noise from dark current. The electric field change was achieved by changing the laser-RF phase.

The thermal emittance increases following the QE change were observed, and shown in Fig. 3 are the thermal emittances by 23% after contamination measured at 25.7 MV/m (40 deg gun phase). Emittance data shown in Fig. 3 includes 95% of the beam particles.

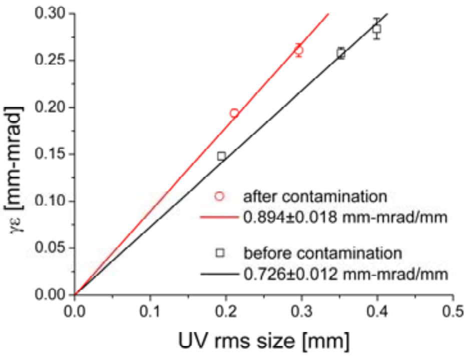

Figure 3: Thermal emittance (at 25.7 MV/m) increase after contamination.

The thermal emittance after contamination are measured with only two laser sizes due to time limit, and thermal emittance are calculated with linear fit by forcing the curve going through the origin. The thermal emittances are then fitted to Eq. (6) (see Fig. 4), and fitting results are listed in Table 1. Due to the physical meaning of field enhancement factor, it is better to fit the cathode parameters with emittance including 100% of the beam particles. The fitting result reveals huge emittance contributions from surface roughness effect. According Eq. (4), a surface roughness with period of 4 μm and amplitude of 100 nm will make such a roughness emittance. In future we will measure more data to make the emittance results more reliable, and cathode plate will be sent for surface roughness analysis.

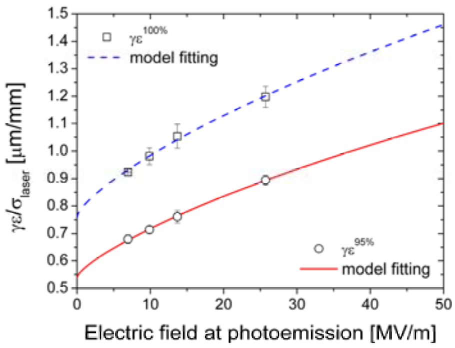

Figure 4: Fitting of thermal emittance (after contamination) to electric field.

Table 1: Cathode Parameters Extracted by Thermal Emittance Fitting

item	$\gamma\varepsilon^{95\%}$	$\gamma\varepsilon^{100\%}$
$\hbar\omega-\phi_w$	0.44 eV	0.88 eV
β	0.92	3.62
Surface roughness emittance @ 50 MV/m	0.87 μm/mm	1.11 μm/mm

SUMMARY

We proposed to study the online cathode parameters by doing electric field dependence of QE and thermal emittance measurement. A contaminated copper cathode has been studied with this method, and was showed to have a lowered work function. This is supported by observation of increase of QE and thermal emittance. Besides, surface roughness emittance was also experimently revealed for the first time.

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