EXPERIMENTAL STUDIES OF THERMAL EMITTANCE OF THE MG CATHDOE AT THE NSLS SDL*

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Abstract

With a large difference between the work function (3.66 eV) and photon energy (4.66 eV), Magnesium (Mg) cathode is a good candidate for thermal emittance studies. Mg cathode has been in operation at the NSLS Source Development Lab (SDL) since 2004, and we have been routinely operating the Mg cathode with quantum efficiency (QE) better than $1x10^{-4}$, while the best QE we observed is about $2x10^{-3}$. We have carried out systematic experimental studies of transverse emittance of the Mg cathode in a photocathode RF gun, and the measured thermal emittance of the Mg cathode is better than that of Copper (Cu) cathode reported in the literature [1]. We also observed almost no thermal emittance change as the QE of the Mg cathode varied from 10^{-4} to 10^{-3}. Our experimental results could not be explained by the 3-step volume photoemission model, and they contradict the popular thermal emittance formula prediction.

INTRODUCTION

Electron beam brightness, especially emittance, is critical for the hard X-ray free electron laser (XFEL) sources, and its power has been witnessed through the revolutionary success of LCLS [2]. With more demands for the XFEL sources from the science community, continuous efforts have been spent to improve the beam brightness to make XFEL facility more compact and cost efficient. In state of the art photoinjectors, thermal emittance has become the ultimate limit of beam brightness [3], thus thermal emittance optimization is important for beam brightness improvement. An ideal photocathode for the purpose of XFEL is expected to have a low thermal emittance, high QE, and long life time, and current photocathodes employed in XFEL photoinjectors still need optimizations, which require both experimental and theory investigations of thermal emittance. This paper reports an experimental characterization of thermal emittance and its QE dependence for Mg cathode at NSLS Source Development Laboratory (SDL).

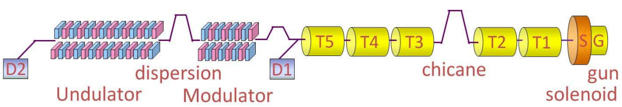

Figure 1: The NSLS SDL schematic layout.

The NSLS SDL is a laser linac facility dedicated to the high-brightness electron and photon beam R&D and applications [4]. SDL consists of a BNL type photocathode RF gun, a 300 MeV linac, a four-magnet chicane bunch compressor and a FEL system (fig.1). Inside the RF gun is an Mg cathode which is embedded in the center of a Cu substrate by frictional welding technique, as shown in Figure 2. Besides, a frequency tripled Ti:sapphire laser system based on chirped pulse amplification (CPA) sends a 266 nm UV laser to the gun to generate photoelectrons, and a 800 nm IR laser to the undulator for seeded FEL.

According to the theoretical study of metal cathode photoemission based on the three step model [5], QE and thermal emittance are predicted to have a quadratic and an evolution relationship with photoelectron excess kinetic energies respectively, and formulized as in Eq. (1) and (2).

$$QE \propto (h\nu - \phi_{eff})^2 \qquad (1)$$

$$\varepsilon_{th} \propto \sigma_t \sqrt{h\nu - \phi_{eff}} \qquad (2)$$

In which, $h\nu$ is the photon energy, ϕ_{eff} is the effective work function, and σ_t is the rms transverse laser spot size. The above theory predicts "both the QE and emittance decrease with increasing effective work function suggesting the disappointing result that to reduce the emittance one has to accept a lower QE" for a metal cathode [5]. Under this guideline, thermal emittance reduction of Cu cathode has been demonstrated by tuning photon energy while sacrificing QE [6]. Nevertheless, most experimental thermal emittance results are consistently much larger than theory predictions [7], thus Schottky effect, surface roughness and non-uniform QE have been investigated to explain such a difference [8, 9, 10]. In this paper, it is shown that, the experimental Mg thermal emittance is not only much smaller than theory prediction, but also almost independent of QE variation as much as a factor of 10.

In the following, the performance of an Mg cathode at SDL is presented first; we then introduce our experiment strategy; at last, we will present the experiment results.

MG CATHODE

Due to a large difference between the work function of Mg (~3.6 eV) and UV laser photon energy (4.66 eV) used in most photoinjectors, Mg cathode is known for its high QE among metal cathodes, but is expected to have a much higher thermal emittance than Cu, whose work function (~4.6 eV) is much closer to the photon energy, according to equation (2). Besides, due to its active chemical properties, Mg cathode fabrication and its high QE maintaining is also very challenging, so Mg cathode is not

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as widely used in photoinjectors as Cu cathode. At BNL, a set of technologies for Mg cathode fabrication, operation and high QE restoration have been developed [11, 12]. Typically, Mg cathode operation requires a vacuum on the order of 10^{-10} Torr in order to keep a QE above 10^{-4} for months. When Mg QE drops to 1×10^{-4} gradually, vacuum based laser cathode cleaning technique will be used to restore the high QE in situ by usually one order of magnitude [12]. Figure 2 plots the QE measurements of the Mg cathode one day after a cathode cleaning, and QE of 2×10^{-3}, outside the space charge region, is the highest reported for a metal cathode. QE higher than 1×10^{-3} usually lasts about 1~2 weeks, and then stabilized around 6×10^{-4} for months before it drops to 1×10^{-4}. With a good vacuum and laser cathode cleaning technique, the same Mg cathode has been used since 2004, demonstrating its robustness.

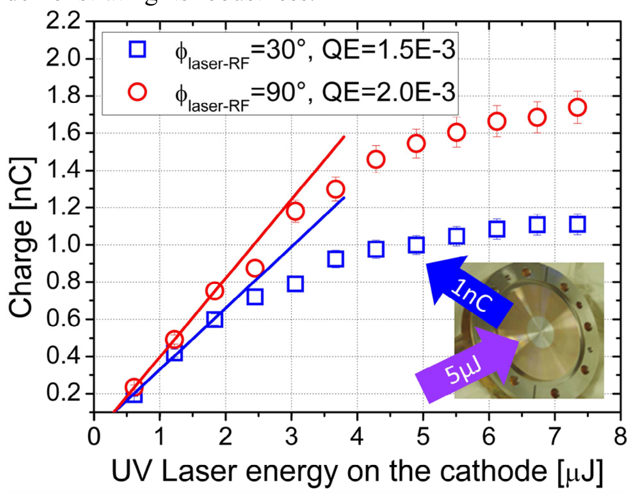

Figure 2: QE measurement of the Mg cathode at RF gun phases 30 and 90 degree for a 100 MV/m field.

EXPERIMENT STRATEGY

The beam emittance is measured by quadruple scan technique at tank2 exit (Figure 1). QE is calculated by measuring the charge with a Farady cup just after the gun and the laser energy in the laser room.

Conceptually speaking, the total emittance of the electron beam generated by a photocathode RF gun can be divided into three parts, which are thermal emittance, RF emittance and space charge emittance [13]. To explore the thermal emittance, we have to minimize the other emittance degrading factors. To lower the nonlinear space charge effect, we shaped the transverse laser profile into a quasi-uniform distribution, and beam charge was also lowered to 10~20 pC, which is almost the limit of SDL imaging instrumentation. To lower the linear space charge effect, we optimized the emittance compensation by solenoid focusing and booster gradient scanning. Besides, we also varied the electron beam bunch length by scanning gun phase and laser pulse length, and it is found that emittance gets reduced with a shorter bunch length.

After all the optimizations, the emittance measurement conditions are listed in Table 1. It is found by PARMELA simulation that the measured projected emittance is still bigger than thermal emittance, i.e. other factors still contribute to the emittance growth, especially in the head and tail part, where the nonlinear space charge effect is most severe. In order to correct those factors, PARMELA simulations are done to find the thermal emittance by fitting the measurement results and simulation results, while thermal emittance calculation by direct linear fitting of measured projected emittance against laser spot size is not proper here.

Parameter	Value	Unit
UV transverse distribution	uniform	
UV longitudinal distribution	Gaussian	
UV pulse duration (FWHM)	10	ps
Charge	10~20	pC
rf gun gradient	100	MV/m
gun phase ($sin(\theta_1)$)	10	deg
tank1 gradient	11	MV/m
tank1 phase ($cos(\theta_2)$)	-40	deg
tank2 gradient	11	MV/m
tank2 phase ($cos(\theta_3)$)	40	deg
cathode to tank1 entrance	90	cm

Table 1: Optimized beamline parameters.

Quad-scan is the main tool in our emittance measurement, and emittance is calculated by least square fitting. To improve the resolution and stability of the quad-scan technique, we have studied the sensitivity of the emittance fitting result on minimum beam size during quad-scan, beam size fluctuation, beam size measurement error, and so on. It is found that to make emittance fitting result more accurate and stable, beam size fluctuation should be much smaller than minimum beam size during quad-scan, and the beam size scan range should be around a factor of 2. So, during the emittance study experiment, we always stabilize our machine as much as we can, the typical laser intensity stability is ~5% (RMS), and laser to RF sync stability is ~0.5 ps (RMS). Besides, the drift space in the quad-scan is maximized to be ~7.3 m, and beam line lattice is tuned to make sure the minimum RMS beam size during the quad-scan is always above 100 um. After all these efforts, fluctuation error bar of our emittance fitting result is always below 10%.

In order to study the QE dependence of thermal emittance for Mg cathode, emittance need to be measured before and after the cathode cleaning, corresponding to low QE and high QE. If cathode cleaning is not properly implemented, it will cause QE non-uniformities, which will cause emittance growth due to nonlinear space charge effect. In this case, solenoid imaging of the beam distribution from cathode to a YAG screen downstream the gun solenoid is used to check the QE uniformity. For example, QE non-uniformity was accidently created during one cathode cleaning, as shown in Figure 3, and emittance growth was observed. After the QE modulation was removed by a second cathode cleaning, the emittance growth disappeared. This not only demonstrates that QE non-uniformity will cause emittance growth, but also the validity and resolution of our quad-scan technique.

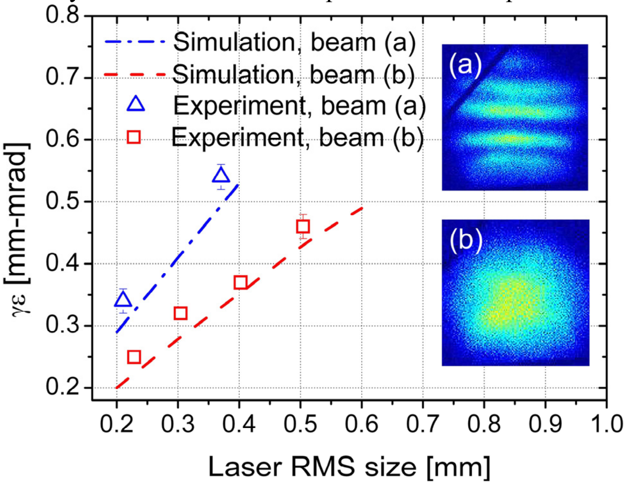

Figure 3: Emittance of a 20 pC electron beam with QE modulation (a) and without QE modulation (b).

EXPERIMENT RESULTS

During the thermal emittance study experiment, we varied the UV radius on the cathode between 1 mm and 0.4 mm, and the projected emittance is measured for each UV spot size. PARMELA fitting of the measurement results indicates the thermal emittance of Mg in the lower QE (10^{-4} torr) case is 0.5 mm-mrad per mm of the rms laser size, as shown in Figure 4. Assuming a work function of 3.66 eV for Mg and the field enhancement factor to be 1, the thermal emittance calculated by equation (2) is 0.9 mm-mrad/mm, which is much higher than the experiment result. Besides, emittance measured in the higher QE (10^{-3} torr) case is almost the same with that in the lower QE case (Figure. 4), while equation (1) and (2) predicts an thermal emittance increase of 80% ($10^{1/4}$-1) compared with the lower QE case (10^{-4} torr). Both the thermal emittance value itself and its dependence on QE contradict the theory prediction.

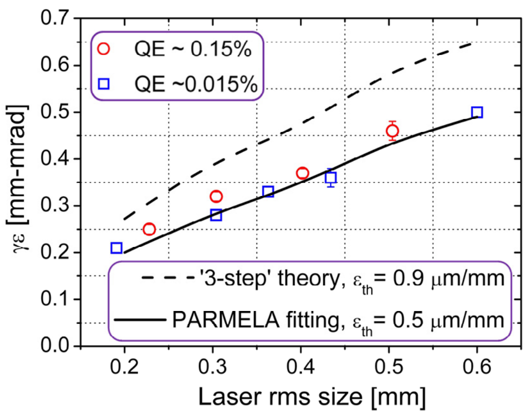

Figure 4: Emittance as a function of laser spot size for a QE of 0.15% and 0.015%; a theoretical prediction based on reference 5 is also included.

CONCLUSION

Thermal emittance is systematically studied for a Mg cathode in a photocathode RF gun for the first time, and the measurement result of 0.5 mm-mrad/mm is much lower than theory prediction (0.9 um/mm). Besides, when the Mg cathode QE is varied by a factor of 10 with laser cathode cleaning technique, almost no change of emittance is observed in the experiment, while the theory predicts an increase of thermal emittance by 80%. Both experiment results cannot be explained by the 3-step model volume photoemission theory, and are still under investigation. Our experiment breaks the current thermal emittance theory prediction for metal cathode, and has demonstrated the feasibility of the coexistence of low thermal emittance (0.5 mm-mrad/mm) and high QE (10^{-3}) on the Mg cathode.

ACKNOWLEDGEMENTS

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