HIGH-BRIGHTNESS ELECTRON BEAM STUDIES AT THE NSLS SDL*

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Abstract

Experimental optimization of electron beam brightness at the NSLS SDL is reported in this paper. Using a high quantum efficiency (QE) Mg metal cathode and the S-band BNL-type RF gun, we have systematically studied electron beam's transverse and longitudinal emittance. The measured thermal emittance for the Mg cathode is 0.85±0.04 mm-mrad/mm, which contradicts the current thermal emittance model. For a 50 pC beam, measured normalized transverse and longitudinal RMS emittance are 0.6 mm-mrd and 5.2 ps-keV, respectively. The smallest projected transverse emittance observed for a 20 pC charge is 0.15 ± 0.02 mm-mrad.

INTRODUCTION

There is a growing interest in optimizing the electron beam for X-ray FEL (XFEL) and other applications. In the earlier design studies of the XFEL [1-2], electron beam with a charge on the order of 1 nC was adopted for the base line operation. The experimental results from both beam studies [3] and FEL saturation [4] show that an electron beam with a charge ranging 40~200 pC possess much higher brightness and leads to a better FEL performance. Further more, interest in generating ultra-short FEL pulse also leads electron beam optimization towards charge of a few pC [5-6]. This paper reports the progress of recent experimental optimization of electron beam for the XFEL applications at the NSLS Source Development Laboratory (SDL).
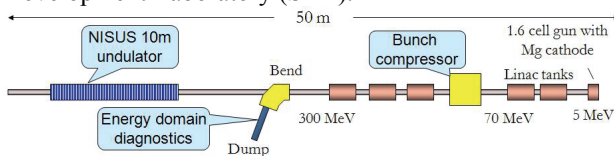

Figure 1: The NSLS SDL schematic layout.

The NSLS SDL is a laser linac facility dedicated to the high-brightness electron and photon beam R&D and applications [7]. SDL consists of a high-brightness 1.6 cell BNL type photocathode RF gun, a 300 MeV linac, a four-magnet chicane bunch compressor and a FEL system (fig.1). In a typical SDL operation, electron beam with a charge of 350 pC to 1 nC is first generated by the RF gun at about 5 MeV, and then accelerated to 70 MeV. After introducing an energy chirp, the electron beam is compressed by the bunch compressor, the compressed electron beam is then accelerated again to remove any

residual energy chirp and to the beam energy FEL requires. Recent SDL studies [8] also demonstrated a significant energy spread and transverse emittance growth during the bunch compression for the electron beam with a charge higher than 500 pC. Based on the earlier BNL studies [3-5] and recent experimental results from LCLS [9], it is imperative to revisit the electron beam optimization algorithm for XFEL, and a systematic electron beam optimization in 6-D phase space for a charge ranging from 20 to 100 pC could lead to a better and cost effective XFEL in the future. We report the progress of our experimental studies of electron beam optimization in this paper. In the following, the electron beam performance of an Mg cathode is presented first; we then discuss the experimental results of the electron beam optimization and thermal emittance as a function of laser (spot size and pulse length), RF gun phase and charge. We will also briefly describe our future R&D plan.

MG CATHODE

Copper and Mg are two most popular metal cathode materials. Copper is the choice for LCLS [1] and other short wavelength FEL because of the concern of thermal emittance. But our experience in FEL [4] and understanding of the photoemission process in a metal cathode under the RF field contradict to this popular belief. Mg cathode is an ideal test case for thermal emittance studies because of relative large difference between the work function (<3.7 eV) and photon energy employed (4.6 eV). Figure 2 plots the quantum efficiency (QE) measurements of the Mg cathode after a vacuum based cathode surface cleaning. The measured QE 0.12 % is the highest for a metal cathode, and could last over a month if the RF gun vacuum is kept below 5×10^{-10} Torr. Cathode cleaning not only increases the QE by at least an order of magnitude, but also improves the QE uniformity.
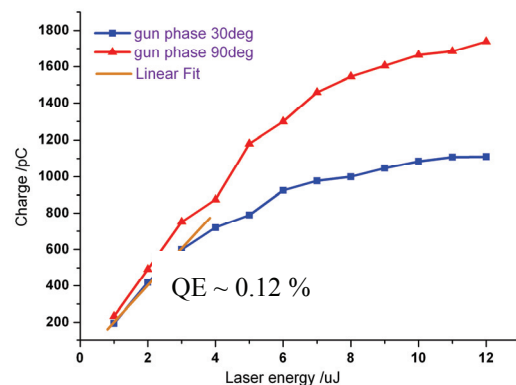

Figure 2: QE measurement of the Mg cathode at RF gun phases 30 and 90 degree for a 100 MV/m field.

Figure 3 shows the transverse laser profile and the intensity distribution across a single horizontal line. The quasi-uniform laser profile is generated by truncating a Gaussian distribution. The laser profile has an intensity fluctuation of 50% ~ 60% (p-p).
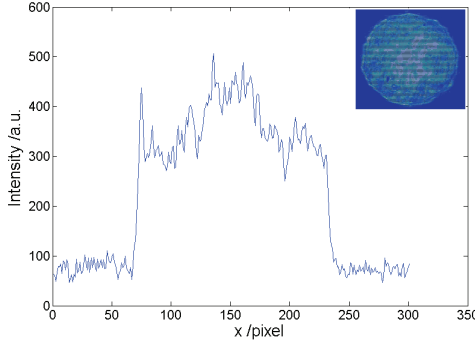

Figure 3: UV Laser transverse profile and intensity projection on a horizontal line

EMITTANCE OPTIMIZATION

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. It is well known that emittance growth of different components is correlated, and growth rate is proportional to the initial emittance [10]. To explore the fundamental limit of various emittance sources, we first consider a charge of 20 pC to minimize the space charge effect. The RF induced transverse emittance can be estimated by the following equation [11],

$$\varepsilon_x^{rf} = \frac{1}{\sqrt{2}} \alpha k \sigma_x^2 \sigma_\phi^2 \qquad (1)$$

Where α is a dimensionless parameter representing the strength of the accelerating field, k is the RF wave number, σ_x and σ_ϕ are the transverse and longitudinal RMS size of the electron beam, respectively. Eq. (1) shows the feasibility of minimizing the RF emittance by controlling the photocathode laser parameters.

To minimize the space charge effect, the emittance measurement should be done with high electron beam energy. On the other hand, higher energy will lead to smaller geometric emittance, which will be more suspicious to experimental error. The beam energy between 70 and 100 MeV is a good compromise for our conditions.

Quad-scan is the main tool for our experiment, and multi-screen method provides a cross check. To extend the dynamic range of the quad-scan technique, we have commissioned a 10-bit frame grabber recently at the SDL.

Figure 4 shows the experimental results of transverse emittance as a function of the RF gun phase for a charge of 20 pC. 20 pC is almost the limit for the SDL beam instrumentation. The strong dependence of the emittance on the RF gun phase is largely due to the electron beam ballistic bunching inside the RF gun cavity [3].

Figure 4 shows that operating the photocathode RF gun at a lower phase is critical for optimizing the electron beam brightness. Both transverse and longitudinal emittances of the electron beam with a charge of 50 pC were measured at the RF gun phase of 15 degree. The normalized transverse and longitudinal rms emittance are 0.6 mm-mrd and 5.2 ps-keV, respectively.
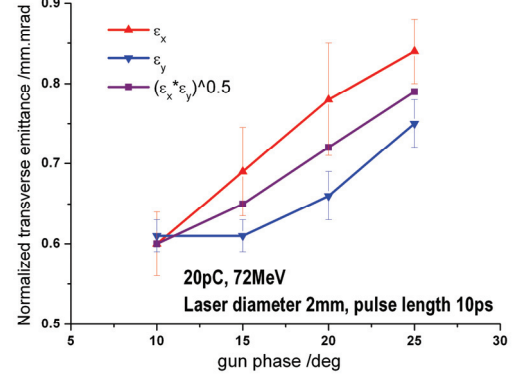

Figure 4: Transverse emittance versus the RF gun phase.

There are several formulas related to the thermal emittance, it could be expressed in the following form [12, 13],

$$\varepsilon_x^{thermal} = \sigma_x \sqrt{\frac{h\nu - \phi_{eff}}{\chi mc^2}} \qquad (2)$$

Where $h\nu$ is the photon energy, ϕ_{eff} is the effective work function of the cathode under the RF field, and χ ranges from 1 to 3 for different models. The linear dependence of the thermal emittance on the laser spot size differentiates it from the RF and space charge effects. Besides, the thermal emittance should be independent of the laser pulse length.
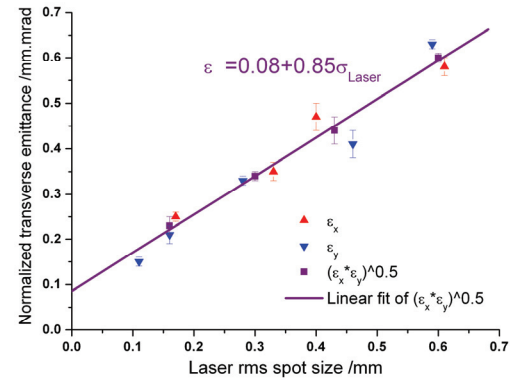

Figure 5: Transverse emittance versus the laser rms size

We performed the electron beam transverse emittance measurements as a function of the laser spot size. The first measurement is done with a 10 ps (FWHM) UV laser, and a linear fit of measurement results shows an upper limit of 0.85 ± 0.04 mm-mrad/mm for the thermal emittance of the Mg cathode, and a residual of 0.08±0.02 mm-mrad may come from the RF and space charge effects, and experimental measurement errors.

We also investigated the laser pulse length effect by reducing it to 5 ps (FWHM). The 5 ps case shows little decrease of emittance comparing to the 10 ps case, as shown in figure 5. This means the gun compression, at 10 deg is good enough to make the RF induced emittance negligible for the 20 pC beam. In the 5 ps case, the linear fit of the data shows an upper limit of 1.04 ± 0.08 mm-mrad/mm for the thermal emittance and a residual of 0.03 ± 0.03mm-mrad.
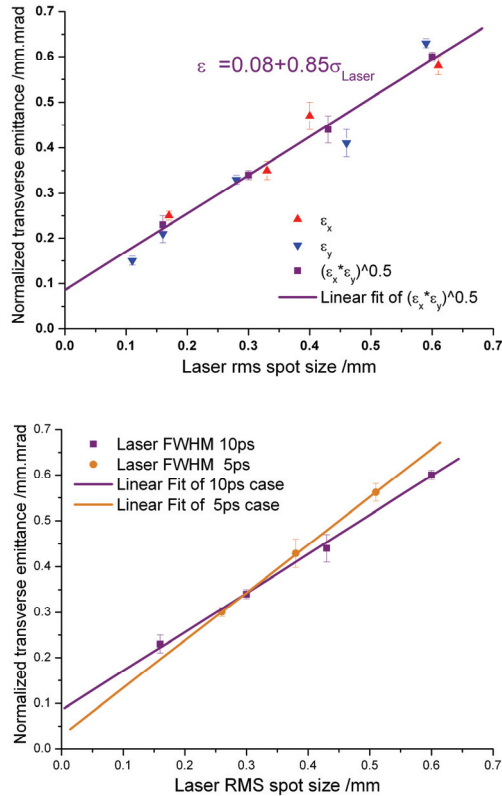

Figure 6: Comparison of transverse emittance between the 10 ps and 5 ps laser pulse lengths.

Our experimental results are consistent with previous measurement results [14], and one interesting fact is that the same level thermal emittance upper limit (~0.9mm-mrad/mm) has also been measured for Cu cathode [9, 15]. According to equation (2), thermal emittance of the Mg cathode should be much larger than copper cathode, which contradicts the experiment results. If χ equals 3 and field enhancement factor of 5 is used in equation (2), the calculated thermal emittance is 0.94 mm-mrad/mm when Laser illuminates the Mg cathode at 10 degree RF gun phase with a peak field of 100MV/m. Since the slice emittance at the core part of the electron beam is smaller than the projected emittance [9], the thermal emittance upper limit should be even smaller than 0.85 mm-mrad/mm which is calculated by projected emittance and

this is against the current theory predictions. This discrepancy between experiment and theory prediction is still under investigations.

CONCLUSION

Electron beam brightness has been optimized in the low charge regime using the NSLS SDL photoinjector. For a 50 pC beam, measured normalized transverse and longitudinal RMS emittance are 0.6 mm-mrd and 5.2 ps-keV, respectively. The smallest projected transverse emittance observed for a 20 pC beam is 0.15 ± 0.02 mm-mrad for a RMS laser spot size of 0.1 mm.

We also investigate the thermal emittance of an Mg cathode. A thermal emittance upper limit of 0.85±0.04 mm-mrad/mm was observed for the Mg cathode, which contradicts the current theory predictions. The discrepancy between theory and experiment is still under investigation.

We intend to continue our experimental effort to optimize the electron beam at the NSLS SDL with a goal of achieving transverse emittance smaller than 0.1 mm-mrad. We will also explore both ballistic and magnetic compression techniques to generate ultrashort electron pulses. More experimental studies on low charge high brightness beams are underway.

ACKNOWLEDGEMENTS

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