An emittance measurement device for a space-charge dominated electron beam*

WANG Wen-Jing(王文静)1) HUANG Sen-Lin(黄森林)
QUAN Sheng-Wen(全胜文) LIN Lin(林林) LIU Ke-Xin(刘克新)2)

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China

Abstract: Beam emittance is one of the most important parameters for electron sources. To investigate the beam emittance of the 3.5-cell DC-SC photocathode injector developed at Peking University, a multi-slit emittance measurement device has been designed and manufactured. The designed slit width, mask thickness and beamlet drift length are 100 μm, 3 mm and 430 mm respectively. It is suitable for the electron beam with energy of about 5 MeV and the average current less than 0.1 mA. The preliminary measurement result of the rms emittance of the electron beam produced by the DC-SC injector is about 5–7 mm·mrad.

Key words: emittance measurement, multi-slit, space charge effect, DC-SC photocathode injector

PACS: 29.27.Fh **DOI:** 10.1088/1674-1137/36/9/013

1 Introduction

The DC-SC photocathode injector is one of the new candidates to produce a low-emittance, high-brightness electron beam. Its design, which integrates a Pierce DC gun and a superconducting cavity, was first proposed by Peking University [1]. It was preliminarily demonstrated by the beam experiments at 4.4 K with a prototype consisting of a Pierce gun and a 1.5-cell cavity [2].

Recently, an upgraded DC-SC photocathode injector with a 90 kV Pierce gun and a 3.5-cell superconducting cavity was designed and manufactured as the electron beam source for the Energy Recovery Linac facility at Peking University [3]. This injector is expected to generate a high average current and low-emittance electron beam. In order to monitor the emittance of the electron beam produced by the DC-SC injector, a dedicated emittance measurement device is necessary. In this paper, we describe the design and manufacture of this dedicated emittance measurement device as well as the preliminary measurement results.

2 The method of electron beam emittance measurement

The method of emittance measurement can be classified as direct and indirect ones. Direct measurements use a metal slit or grid to stop the beam, such as the single-slit, multi-slit mask and "pepper-pot" method. Only a few portions of electrons pass through the slit or grid and form several beamlets. The traverse profile of the beamlets is then detected at some downstream location. The direct method can be used to measure the emittance of both the space-charge dominated beam [4–6] and emittance dominated beam. Indirect measurements, such as the multiple profile monitor and variable quadruple strength method, are based on the linear beam transport theory and only apply to the emittance dominated electron beam.

When considering the space charge effect, the rms envelope equation [7] for a round electron beam in drift space is

$$\sigma_0'' - \frac{\varepsilon_{\rm n}^2}{\gamma^2\sigma_0^3} - \frac{2I}{I_0\gamma^3\sigma_0} = 0, \tag{1}$$

Received 2 November 2011

* Supported by Major State Basic Research Development Program of China (2011CB808302) and Peking University grant for interdisciplinary or developing disciplinary studies

1) E-mail: wenjing_wang@pku.edu.cn

2) E-mail: kxliu@pku.edu.cn

where σ_0 is the beam envelope, ε_n is the normalized emittance, γ is the Lorentz factor, I is the peak current and I_0=17 kA is the Alfven current. The ratio of the third to the second terms on the left hand side of Eq. (1) gives a measure of the space charge effect, which can be expressed as

$$R_0 = \frac{2I\sigma_0^2}{I_0\gamma\varepsilon_n^2}, \tag{2}$$

When R_0 is much less than 1, the electron beam is emittance dominated and can be dealt with by the linear transport theory. If R_0 is much larger than 1, the electron beam is space-charge dominated. To measure the emittance of the space-charge dominated electron beam, space-charge force must be considered.

The designed parameters of the electron beam produced by the 3.5-cell DC-SC photocathode injector are I=12 A, σ_0=3 mm, E=5 MeV, and ε_n <3 mm·mrad. Accordingly, R_0 is 130 and the electron beam is space-charge dominated. Therefore, we use the multi-slit method to measure the beam emittance of the DC-SC injector.

3 Parameters of multi-slit emittance measurement device

The main parameters of a multi-slit emittance measurement device, which is shown in Fig. 1, include slit width, mask thickness, slit separation and beamlet drift length.

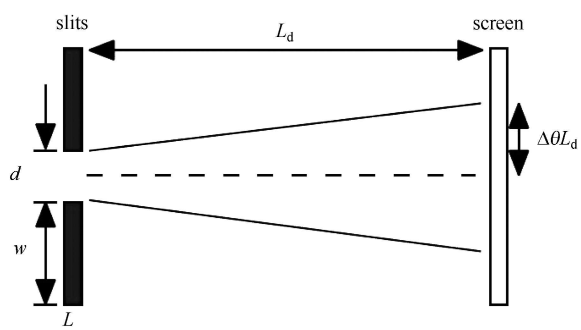

Fig. 1. A schematic view of multi-slit emittance measurement device, d is the slit width, w is the slit separation, L is the multi-slit mask thickness and L_d is the beamlet drift length.

The multi-slit should allow some electrons to pass through it to form beamlets and then the cross section of the beamlets can be measured in the downstream. With the beamlet profiles, we can reconstruct the original beam's transverse distribution and calculate the emittance. When a space-charge dominated electron beam passes through the multi-slit, most of the electrons are intercepted by the mask, only leaving several beamlets to pass through the slits. Therefore, the space-charge forces are reduced remarkably and can be ignored. In principle, it is better to make the slits as small as possible. But considering the limitation of machining, 100 μm has been chosen for the slits width.

The mask should be thick enough to fully stop the electron beam. The stopping length of the electrons in certain material can be approximated by

$$L = \frac{E}{\frac{dE}{dx}} = \frac{E[\text{MeV}]}{1.5[\text{MeVcm}^2\text{g}^{-1}]\rho[\text{gcm}^{-3}]}, \tag{3}$$

where ρ is the material density and E is the energy of electrons. Table 1 shows the mask thickness of different materials needed to stop the electrons with the energy of 5 MeV.

Table 1. The required thickness of mask made of different materials to stop a 5 MeV electron beam.

	Fe	Cu	Mo	W
density/(g/cm^3)	7.86	8.92	10.29	19.35
thickness/mm	4.24	3.74	3.27	1.72

Mo is chosen as the slits mask material because it has a higher melting point than Fe and Cu, better thermal conductivity than stainless steel and is easy to machine compared with W. Therefore, the thickness of the slits mask is 3 mm.

Slits separation and beamlet drift length were determined with the following criteria for designing the multi-slit emittance measurement device:

1) The angular acceptance of the slits must be significantly larger than the original beam divergence, i.e.

$$R_1 = \frac{2L}{d}\frac{\varepsilon}{\sigma} \ll 1.$$

2) The width of the beamlet on the screen must be much larger than the slit width. Using R_2 to represent the ratio of the width of the beamlet on the screen to the slit rms width, this criterion can be written as

$$R_2 = \frac{2\sqrt{3}}{d}\frac{\varepsilon}{\sigma}L_d \gg 1.$$

3) The beamlet width on the screen has to be smaller than the distance between two neighboring beamlets on the screen, i.e.

$$R_3 = \frac{L_d}{w}\frac{\varepsilon}{\sigma} \ll 1,$$

where R_3 is the ratio of the beamlet width on the screen to the distance between neighboring beamlets.

4) The inter-beamlet space-charge force is small enough that it can be neglected. This criterion can be written as [8]

$$R_4 = \frac{2I}{I_0\gamma^2}\frac{dL_{\rm d}}{w\varepsilon_{\rm n}} \ll 1.$$

The final designed slit width, slit separation, mask thickness and beamlet drift length are 100 μm, 1.5 mm, 3 mm and 430 mm respectively.

4 The electron beam current threshold

Since the electron beam produced by the 3.5-cell DC-SC photo injector have high average currents, large amounts of energy from the electron beam will be deposited in the multi-slit mask during emittance measurements. The resulting thermal diffusion and heat distribution must be considered to prevent the mask from being damaged.

Heat distribution was simulated with the software Solidworks. Uniform heat generated is assumed on a cylinder at the slits mask centre to simulate the electron beam energy deposition in the mask. The thermal radiation is considered and the temperature of the surrounding environment is set to 50 ℃. Fig. 2 shows the temperature distribution on the slits mask with the beam energy of 5 MeV and the average beam current of 100 μA. We also compared the temperature increase at the centre of the mask with different beam currents from 20 μA to 200 μA. The simulation results are shown in Fig. 3. When the beam current is lower than 100 μA, the highest temperature at the mask centre will be lower than 1452 ℃ while the temperature at the edge of the mask will be lower than 1300 ℃, therefore, the mask should not be damaged. This allowable beam current is much lower than the designed average beam current of more than 1 mA for the 3.5-cell DC-SC injector, but the average beam current can be reduced by lowering the repetition rate of the drive laser pulse during emittance measurements.

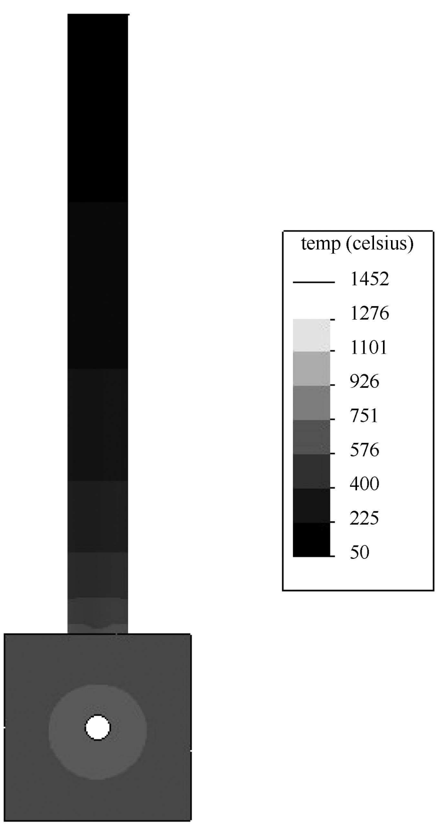

Fig. 2. Temperature distribution on the slits mask with the beam energy of the 5 MeV and the average beam current of 100 μA.

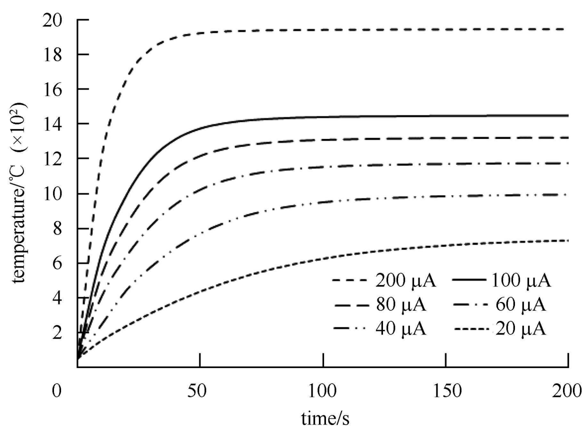

Fig. 3. Temperature increase of slits mask made of molybdenum with different beam currents.

5 The emittance measurement

Two slit masks had been made for measuring the emittance in the X plane and Y plane respectively. There are 13 slits on the mask processed by WEDM (Wire cut Electrical Discharge Machining) and the width of the slit is 87 μm with a fluctuation of 5 μm. The supporting frame is made of stainless steel. Except slit masks, the emittance measurement device consists of a YAG screen and a CCD camera, 3 pneumatic pushers to make the multi-slit masks and the YAG screen up and down, a vacuum chamber and a controller. After assembling and cleaning, it was installed in the test beam line for the DC-SC injector.

The emittance was measured for the electron beam produced by the DC-SC injector with energy of 2.5 MeV and the average beam current of 50 μA.

Fig. 4 shows a typical beamlets cross-section obtained by CCD from the YAG screen. Table 2 lists the calculated emittance for different measurements. Emittance in the X plane is in a range from 5.2 to 6.6 mm·mrad and from 5.2 to 6.9 mm·mrad in Y plane. It can be seen that the measured emittance is higher than the designed value. This is probably because of the non-ideal optimization of the DC-SC injector during this preliminary experiment.

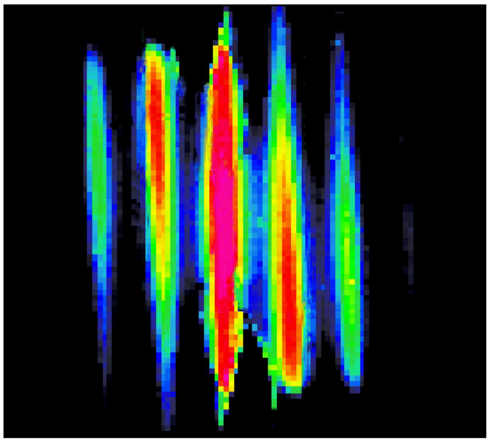

Fig. 4. The typical beamlets for emittance measurement.

Table 2. The emittance results for different measurements.

X plane emittance/ (mm·mrad)	Y plane emittance/ (mm·mrad)
5.2±0.5	5.2±1.0
5.4±1.0	6.3±0.9
6.6±0.6	6.9±1.1

6 Conclution

A multi-slit emittance measurement device has been designed and manufactured at Peking University. The main parameters were chosen carefully to ensure they can be used to measure the emittance of a low energy, space-charge dominated, relatively high average current electron beam. The preliminary measurement results indicate that they are sufficient for monitoring the emittance of the electron beam produced by the DC-SC photocathode injector. The investigation of the beam emittance related to different operating parameters of the DC-SC injector will be carried out in the near future.

References

1 ZHAO Kui et al. Nucl. Instrum. Methods A, 2001, **475**: 564
2 HAO Jian-Kui et al. Nucl. Instrum. Methods A, 2006, **557**: 138
3 ZHU Feng et al. HEP & NP, 2007, **31**(5): 496 (in Chinese)
4 Piot P, SONG J, LI R et al. Proceedings of the 1997 Particle Accelerator Conference, 1998, **1-3**: 2204
5 Evtushenko P, Lehnert U, Michel P et al. Aip Conference Proceedings, 2002, **648**: 313
6 YAN Li-Xin et al. Chin. Phys. Lett., 2008, **25**(5): 1640
7 Reiser M. Theory and Design of Charged Particle Beams. New York: Wiley, 1994, 210
8 Rosenzweig J, Travish G. Design Consideration for the UCLA PBPL Slit-Based Phase Space Measurement Systems, PBPL(1994). http://pbpl.physics.ucla.edu/ Literature/_library/rosenzweig_1994_0350.pdf