MEASUREMENTS OF THERMAL EMITTANCE FOR CESIUM TELLURIDE PHOTOCATHODES IN AN L-BAND RF GUN

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Abstract

The thermal emittance is a major contributor to the final emittance of an electron beam in a photocathode RF gun. In this paper we present measurement results of thermal emittance for the cesium telluride photocathode at the Argonne Wakefield Accelerator (AWA) facility using the quadrupole-scan method. Measurements of the thermal emittance vs. the laser spot size are presented.

INTRODUCTION

Cesium telluride (Cs_2Te) has been used as a cathode in RF photo injectors in the last twenty years. It has a relatively long lifetime (months) and a high quantum efficiency ($\sim 5\%$), and is robust in a high gradient environment [1]. It is used at the AWA for drive beam generation, in which an electron bunch train of 1-32 bunches with a maximum total charge in the trains of 600 nC is produced. In order to further understanding of the Cs_2Te cathode properties, a thermal emittance measurement was conducted on the AWA drive beamline using the quadrupole scan method. The principle of the quad scan can be simply expressed by the following equation:

$$\left\langle x_i^2 \right\rangle = {R_{11}^i}^2 \left\langle x_0^2 \right\rangle + {R_{12}^i}^2 \left\langle x_0'^2 \right\rangle + 2R_{11}^i R_{12}^i \left\langle x_0 x_0' \right\rangle \qquad (1)$$

where $\left\langle x_0^2 \right\rangle$, $\left\langle x_0'^2 \right\rangle$ and $\left\langle x_0 x_0' \right\rangle$ are beam moments on the entrance of the quadrupole, R_{11} and R_{12} are elements of the transfer matrix between the quadrupole and the screen, $\sqrt{\left\langle x_i^2 \right\rangle}$ is the beam size on the screen. By calculating the transfer matrix elements and measuring the beamsize, we can determine the beam moments $\left\langle x_0^2 \right\rangle$, $\left\langle x_0'^2 \right\rangle$ and $\left\langle x_0 x_0' \right\rangle$ by fittings. The normalized rms emittance can be written as

$$\epsilon_{n,x} = \frac{p}{m_0 c}\sqrt{\left\langle x_0^2 \right\rangle \left\langle x_0'^2 \right\rangle - \left\langle x_0 x_0' \right\rangle^2} \qquad (2)$$

where p is the average momentum of the beam, m_0 is the rest mass of the electron and c is the speed of light in vacuum.

The normalized thermal emittance for semiconductor photocathodes can be written as[2]

$$\epsilon_n = \sigma_l \sqrt{\frac{2E_K}{3m_e c^2}} \qquad (3)$$

where σ_l is the rms laser spot size and $m_e c^2$ is the electron rest energy. E_K is the average kinetic energy of the photoemitted electrons on the cathode, which is expressed as

$$2E_K = \phi_l - E_g - E_a + \phi_{Sch} \qquad (4)$$

where ϕ_l is the laser photon energy, E_g is the gap energy, E_a is the electron affinity energy, and ϕ_{Sch} is the potential barrier reduction due to the Schottky effect. ϕ_{Sch} can be expressed as

$$\phi_{Sch} = \sqrt{\frac{e^3}{4\pi\epsilon_0}\beta E_c \sin\phi_0} \qquad (5)$$

where β is the field enhancement factor, E_c is the maximum applied electric field on the cathode, and ϕ_0 is is the laser injection phase relative to the RF in the gun.

EXPERIMENTAL SETUP

The experiment beamline is shown in Fig. 1. A 1.5 cell photocathode RF gun[3] with Cs_2Te, operating at 1.3 GHz, is employed to produce electron bunches. Bucking and Focusing solenoids are placed symmetrically around the Cs_2Te photocathode and a Matching solenoid is located slightly after the gun exit. Three linac solenoids downstream of the gun are used to further transport the electron beam down for quad scan. No linacs were used for this experiment. A stripline BPM is used to measure the bunch charge with sensitivity of 1 pC. Quads placed downstream were used for emittance scans. A 100 micron thick YAG:Ce screen 3.5 m downstream of Quad4 is used to measure the beam size. The procedure is that the first three quads are set to make the beam sizes at both horizontal and vertical directions to minimal at the same current setting of the last quad. The YAG screen was mounted on a motorized actuator and perpendicular to the beam trajectory. The screen was viewed using a 16-bit intensified CCD (ICCD) camera [PIMAX-1k] with gate mode. The gate mode with gate time 100 ns helps to reduce the strength of dark current and increase the signal-to-noise ratio. A resolution target (USAF-1951) was also installed on the same actuator for calibration, showing a camera calibration of 18 μm per pixel.

A pulsed 1.5 ps-10 ps 248-nm UV laser is used at the AWA. Two Microlens Arrays (MLAs) followed by a Fourier lens were used to homogenize the UV laser spot (see Ref. [4] for more details of the MLA). The homogenized laser beam was then imaged to the cathode plane by a lens ar-

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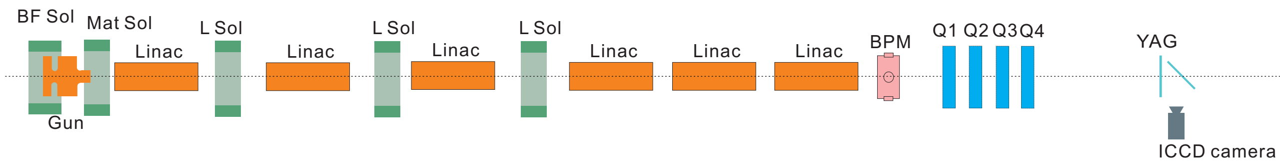

Figure 1: Schematic layout of AWA drive beamline (not to scale).

ray. A homogeneous laser beam would help to reduce the uncertainties in the thermal emittance measurement.

The AWA photocathode RF gun typically operates at 80 MV/m electric field (E_c) on its photocathode surface. For this experiment, E_c was lowered to 50 MV/m in order to reduce dark current. The gun extraction phase ϕ_0 was set to obtain the maximum bunch energy, which is 47° for $E_c = 50$ MV/m. The average beam energy outside the gun is 5 MeV. The laser pulse length was set to the 1.5 ps FWHM, to minimize the RF emittance contribution due to non-linear time variation of the field in the gun to the thermal emittance measurement. We scanned the cathode laser spot sizes from 1.2 mm to 2.5 mm in diameters, and used ASTRA[5] simulation to evaluate the RF induced contribution in the gun. A 3D field map of the gun was used in the simulation, showing that the RF induced emittance growth is negligible for the pulse length of 1.5 ps and spot size from 1.2 mm to 2.5 mm diameter. The bunch charge was set to 1 pC for 2.5 mm laser diameter and the charge density remained the same for other laser spot configurations. This is a compromise between the signal-to-noise ratio for image processing and the space charge effects in the measurement. Based on the ASTRA simulation, the space charge effect is negligible before the quad scan section. But the space charge effect should be carefully evaluated in the quad scan section due to the low beam energy (5 MeV) and small waist beamsize ($\sim 300\mu$m rms). ASTRA simulation showed that we overestimated the emittance by about 10% with the consideration of space charge effect in the quad scan section.

IMAGE ANALYSIS

Precise electron beamsize measurement is critical in emittance calculation. In this section we explain the image analysis used to calculate the beamsize. In Fig. 2, six typical transverse beam images for six different quadrupole settings are shown. The quadrupole gradients are indicated in each image.

We calculated the average pixel value of the background area as the background level of the entire image. The background was subtracted from each image to reduce the pixel noise influence of the ICCD camera on beamsize calculation. There are two optional methods to calculate the beamsize, including rms of the bunch profile and Gaussian fit. The projections to horizontal and vertical directions of the image and the Gaussian fits are indicated in Fig. 2, showing that the projections and the Gaussian fits coincide well. That

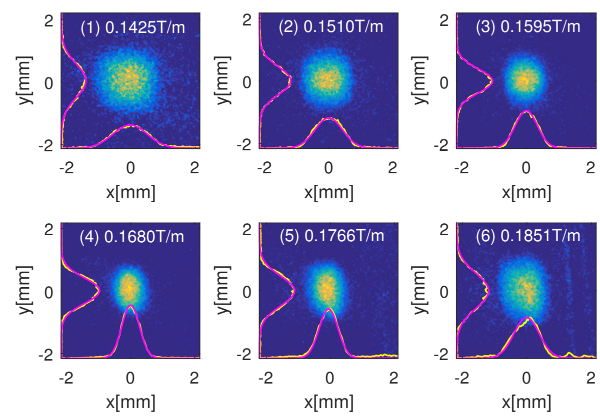

Figure 2: Six typical transverse beam images for six different quadrupole settings. The quadrupole gradients are indicated in each image. The yellow lines are the projections to the horizontal and vertical axes and the pink lines correspond to the Gaussian fits.

means the bunch transverse distribution has a smooth and Gaussian-like profile. We compared the beamsize result between rms calculation and the Gaussian fit. It shows that the Gaussian fit is more robust in the image processing, especially when some hot spots or strips of dark current are close to the photoelectron spot (such as the image of Fig. 2(6)). As a result, we calculated the electron beamsize for each image by means of a Gaussian fit in the following calculations.

MEASUREMENT RESULTS

The beamsize at each quadrupole setting was averaged with 10 images to reduce the beamsize fluctuation impact on the curve fitting. After taking the image data and the quad current, a curve fitting based on Eq. 1 is used to calculate the emittance. One of the curve fittings is shown in Fig. 3 with laser spot size 1.5 mm diameter.

Measurements of the thermal emittance vs. the laser spot size are plotted in Fig. 4. Using a linear fitting without intercept at the origin shows that

$$\frac{d\epsilon_{th,x}}{d\sigma_x} = 1.91 \text{ mrad}, \qquad \frac{d\epsilon_{\mathrm{th,y}}}{d\sigma_{\mathrm{y}}} = 2.22 \text{ mrad} \qquad (6)$$

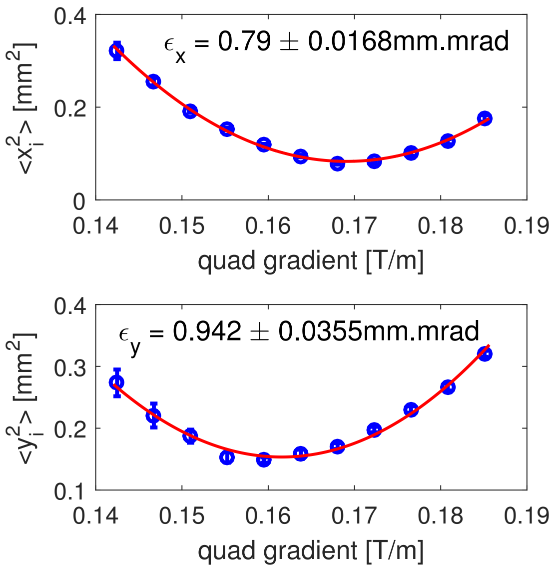

Figure 3: Curve fitting plot for laser spot size 1.5 mm diameter.

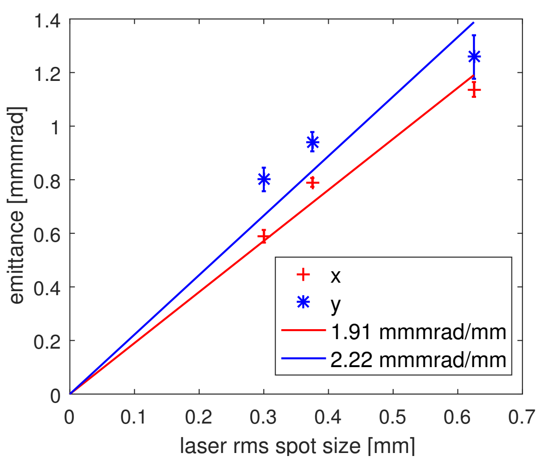

Figure 4: Emittance measurements scaling with laser spot size.

DISCUSSION

Based on Eq.3-5, we estimate the theoretical value of the thermal emittance with our laser photon energy (5 eV) and the applied electric field on the cathode. The electric field on the cathode $E_c = 50$ MV/m, and gun extraction phase $\phi_0 = 47°$. The gap energy E_g is assumed to be 3.3 eV, and the electron affinity $E_a = 0.2$ eV[6]. For a field enhancement factor β between 1 to 5, the theoretical emittance is about 1.1 mmmrad/mm, which is lower than our measurements, this discrepancy is being further investigated at the moment.

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