ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-TUPTS014

SINGLE SHOT CATHODE TRANSVERSE MOMENTUM IMAGING IN PHOTOINJECTORS

P. Huang[1], H. Qian, Y. Chen, J. Good, M. Gross, I. Isaev, C. Koschitzki, M. Krasilnikov, S. Lal, X. Li, O. Lishilin, D. Melkumyan, R. Niemczyk, A. Oppelt, H. Shaker, F. Stephan, G. Vashchenko, DESY, Platanenallee 6, Zeuthen 15738, Germany
W. Wan, Shanghai Tech University, Shanghai 201210, China
D. Fillippetto, F. Sanibale, Lawrence Berkeley National Lab, Berkeley, CA 94704, USA
C. Tang, Tsinghua University, Beijing 100084, China
[1]also at Tsinghua University, Beijing 100084, China

Abstract

In state of the art photoinjector electron sources, cathode performance determines the lower limit of achievable beam emittance. Measuring the thermal emittance at the photocathodes in electron guns is of vital importance for improving the injectors. Traditional methods, like solenoid scan, pepper-pot, need multi-shots and are time-consuming, therefore suffer from machine stability. Here we propose a new method, named cathode transverse momentum imaging. By tuning the gun solenoid focusing, the electrons' transverse momentum at the cathode is imaged to a downstream screen, which enables a single shot measurement. Several experiments have been done at the Photo Injector Test Facility at DESY in Zeuthen (PITZ) with a Cs_2Te cathode. Measurements of cathode transverse momentum, the corresponding spectra, cathode transverse momentum map and its correlation with surface electric field are presented.

INTRODUCTION

Modern accelerator based light sources require extremely small beam emittance to reach high brightness and even the diffraction limit, enabling the exploration of microstructures at atomic level. Low emittance photoinjector electron source is one of the essential technologies for light sources like X-ray free electron laser. Due to the ongoing optimization of gun and laser shaping technologies, the thermal emittance of the cathode dominates the beam emittance [1–3]. Although the thermal emittance is a critical parameter in photoinjector optimization, it is not a routinely measured parameter like gun energy and laser spatial profile in most photoinjectors. Traditional cathode thermal emittance measurements, like solenoid scan or quadrupole scan, rely on fitting projected emittance versus laser beam size and are time consuming, requiring dedicated beam time and good machine stability. Two new methods have been proposed to measure the transverse momentum distribution from cathode [4, 5]. The method in Ref. [5] images the cathode transverse momentum to a focal plane. The method in Ref. [4] does not require a focusing element, and it approximates a downstream beam distribution to momentum distribution by a point like laser spot size at cathode. Both methods are demonstrated in low voltage low gradient DC guns. In this paper, the method in Ref. [5] is applied to a high gradient RF photoinjector and allows routine cathode thermal emittance studies under operation conditions. The simulation proof of the proposed idea and some experiments carried out at the PITZ beam line are presented.

BASIC IDEA

The idea of cathode transverse momentum imaging starts from a common phenomenon in optics beam lines, that is a convex lens can focus the parallel light into one point at the focal plane, shown in Fig. 1. Therefore the image at the focal plane contains the information of the initial direction of light without the coupling of initial position. As an analogy, the dynamics of the electron beam without space charge effect is similar to the optics. The solenoid acts as a convex lens to the electron beam with a Larmor rotation. In accelerator language, the imaging condition is met when the first element in the transport matrix from the cathode to the observation screen is zero, shown as follows

$$\begin{pmatrix} x \\ \frac{p_x}{m_0 c} \end{pmatrix} = \begin{pmatrix} 0 & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} x_0 \\ \frac{p_{x0}}{m_0 c} \end{pmatrix}. \quad (1)$$

Here the matrix works in the Larmor rotation coordinate, decoupling x and y plane. Under this condition, the electron's transverse momentum at the cathode is linearly proportional to its transverse position on the observation screen. A mathematical expression for calculating the normalized cathode transverse momentum can be derived as

$$\frac{\varepsilon_{th}}{\sigma_x(0)} = \frac{\sigma_{p_x}}{m_0 c} = \frac{\sigma_x(L)}{M_{12}}, \quad (2)$$

where ε_{th} is the thermal emittance and $\sigma_x(0)$ and $\sigma_x(L)$ are the root of mean square (rms) spot size at the cathode and screen, respectively. The term, M_{12}, is the second element on the first line of the transport matrix from cathode to the screen. In principle, only a single shot is needed once the imaging condition is found.

It should be noted that the linear correlation between the transverse momentum and the final transverse position has been established under this imaging condition. This relation enables us to obtain the distribution of the emission electrons' transverse momentum which can provide us with more details about the photoemission process and would be helpful to examine different emission models.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-TUPTS014

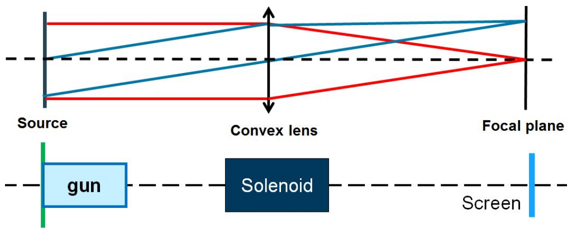

Figure 1: The basic concept of the cathode transverse momentum imaging.

SIMULATION PROOF

Some simulations based on the PITZ beamline have been done by ASTRA [6] to confirm the feasibility of this method. In the simulation, only the PITZ gun and the solenoid are included, followed by a drift to the screen, as shown in Fig. 1. The first thing to be examined is the imaging condition. In simulation, the electron beam is generated with transverse uniform (rms size 0.25 mm) and longitudinal gaussian (7 ps FWHM) distribution, which fits the laser distribution at PITZ. The peak electric field is chosen to be 53 MV/m, corresponding to a final electron momentum of 5.8 MeV/c at the maximum mean momentum gain (MMMG) phase of the gun. The beam was tracked to the position z = 5.28 m, where a highly sensitive LYSO screen is installed in the beam line. The distance is large enough to obtain the proper size of the image. Several starting positions for the beam center on cathode are chosen, as shown in the legend of Fig. 2. The simulation shows that the beams from varied positions overlap with each other on the screen at the same solenoid magnetic field, confirming the imaging condition can be achieved by tuning the solenoid. Here the space charge is switched off.

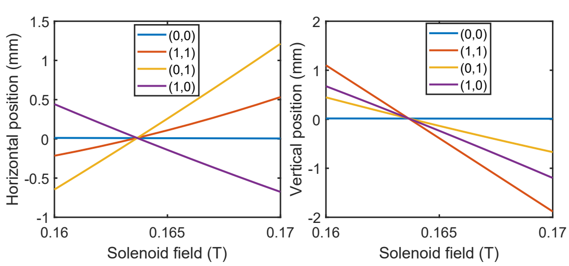

Figure 2: Simulated variation of beam position on the observation screen due to different solenoid field. The legend contains the information of the beam center's initial transverse position with respect to the cathode center. The unit of those numbers in the legend is milimeter.

After determining the required solenoid field, we examine the linear relation between the cathode transverse momentum and the corresponding beam size at the screen. In simulation, several electron files can be generated with different cathode transverse momentum while keeping other parameters the same as above. The results are presented in Fig. 3, showing a good linear fit. The slope in the plot is the value of M_{12}. The results confirm the reliability of Eq. (2).

When the charge is below 100 fC, the space charge effect on M_{12} is small in the simulation. We choose the value of M_{12} from no space charge results.

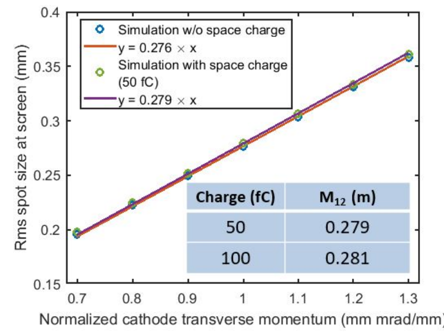

Figure 3: The beam size at the observation screen is in linear proportion to the normalized cathode transverse momentum in simulation with and without space charge. The fitting formula is presented in the legend. Here the solenoid has been set to meet the imaging condition.

EXPERIMENT

Several experiments have been carried out at PITZ. In the experiment, one of the important steps is looking for the desired solenoid current to meet the imaging condition where M_{11} equals zero. M_{11} is measured by trajectory response test. We change the laser position on the cathode and measure the beam movement on the observation screen. The solenoid current is scanned to find the working point for imaging. An example is displayed in Fig. 4. The centroid movement can not reach exactly zero for several reasons. First, the solenoid scan step size is not infinitely small. Second, there are multipole field errors in the gun and solenoid, which will make M_{11} zero at different currents for x and y planes. Third, jitters exist in the machine. When the laser position is moved by 500 µm and the beam centroid movement at screen is below 50 µm, like in Fig. 4, the term, M_{11}, is less than 0.1. Based on Eq. (1), the small M_{11} here contributes to a negligible (<0.5%) overestimation of cathode transverse momentum in our measurement.

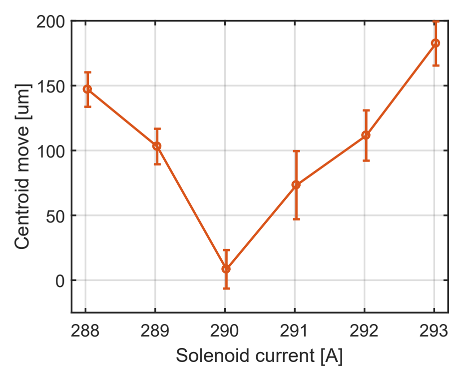

Figure 4: One example of beam movement at observation screen when laser is moved by 0.5 mm vertically at cathode in experiment.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-TUPTS014

Another important step is to search for an operation regime free from the space charge effects since it tends to increase the beam emittance. Under the working condition mentioned in the last section, we find that the space charge can be neglected when the bunch charge is below 100 fC which is consistent with simulations. In the following measurements we keep the bunch charge roughly at 50 fC.

After finding the imaging condition and proper bunch charge, Fig. 5 presents a typical image in the experiment for cathode transverse momentum imaging. The rms size in this image is around 0.27 mm, corresponding to 0.972 mm mrad/mm for normalized cathode transverse momentum. The distribution of transverse momentum on horizontal and vertical direction are also displayed in the figure.

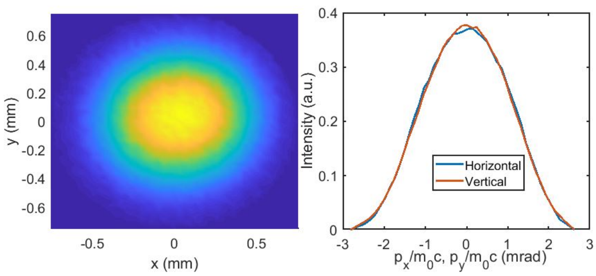

Figure 5: The left figure is a typical image in the experiment for cathode transverse momentum imaging. The right figure is the corresponding transverse momentum distribution on horizontal and vertical axis, respectively.

Electric Field

The electric field on the cathode can change the thermal emittance by Schottky-like and cathode surface roughness effects. By scanning the RF phase, we can achieve different electric fields at the cathode surface when emission happens. The cathode transverse momentum under different electric fields was measured and is presented in Fig. 6. It seems the cathode transverse momentum is quite sensitive to the electric field for this Cs_2Te cathode #661.1. Nearly 60% growth has been observed from 8 MV/m to 50 MV/m. It probably attributes to the contribution of surface roughness. Such dramatic growth was seen on another Cs_2Te cathode at PITZ before [7]. Further investigations are ongoing.

Cathode Transverse Momentum Map

Due to the advantage of single shot measurements, we are able to do a normalized cathode transverse momentum map in a relatively short time. To do the mapping investigation, the RF field's effect on the measurement should be carefully considered, especially for those points far from the cathode center. They will suffer from severe RF kick in the electron gun, leading to an overestimation of the cathode transverse momentum. In simulation, we discover that there exists a special RF phase, MMMG+9 degree, able to reduce this unfavorable effect to less than 1% even at the edge of the cathode. Therefore the mapping investigation is done at this phase. Laser diameter is chosen to be 0.5 mm for a

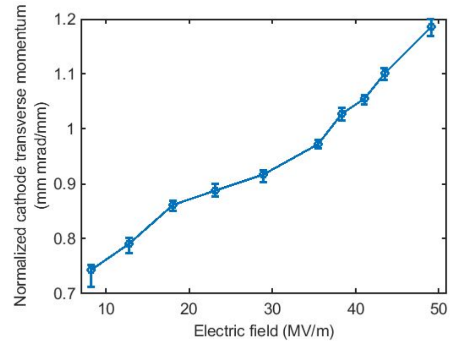

Figure 6: The normalized cathode transverse momentum measured for different electric fields during photoemission.

compromise between better spatial resolution for mapping and space charge effect. Totally 38 data points have been recorded and Fig. 7 shows us an overview of the cathode transverse momentum map of the present Cs_2Te cathode. It seems the routine laser hitting area, located around (0,0), has relatively lower cathode transverse momentum than the cathode edge. This is an interesting phenomenon but the reason still remains unclear. Further investigation is needed to confirm and explain the mapping results.

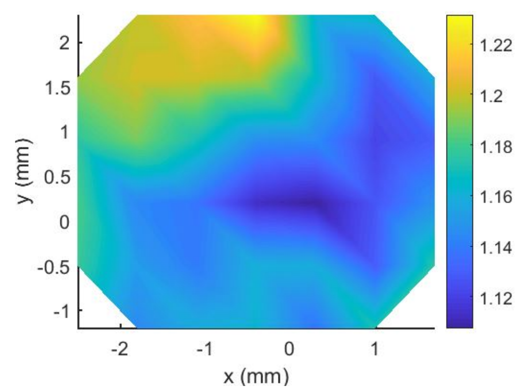

Figure 7: Cathode transverse momentum map of the Cs_2Te cathode. The number next to the color bar refers to the normalized cathode transverse momentum value. The unit is milimeter miliradian per milimeter.

CONCLUSION

A new method to measure cathode transverse momentum of the beam is proposed in this paper. It requires single shot and therefore very convenient and time-saving. Simulation has been done to confirm the feasibility of the idea. Some measurements with this method have been done with a Cs_2Te cathode on the PITZ beam line. We discover that the cathode transverse momentum is very sensitive to the surface electric field. A cathode transverse momentum map of the present cathode is presented and shows slight correlation with the distance to the routine emission area.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-TUPTS014

REFERENCES

[1] D. H. Dowell *et al.*, "Cathode R&D for future light sources", *Nucl. Instrum. Meth. Phys. Res. A*, vol. 622, pp. 685–697, 2010.

[2] M. Krasilnikov *et al.*, "Experimentally minimized beam emittance from an L-band photoinjector", *Phys. Rev. ST Accel. Beams*, vol. 15, p. 100701, 2012.

[3] C. Gulliford *et al.*, "Demonstration of cathode emittance dominated high bunch charge beams in a DC gun-based photoinjector", *Appl. Phys. Lett.*, vol. 106, p. 094101, 2015.

[4] J. Feng *et al.*, "A novel system for measurement of the transverse electron momentum distribution from photocathodes", *Rev. Sci. Instrum.*, vol. 86, p. 015103, 2015.

[5] J. A. Berger *et al.*, "Excited-state thermionic emission in III-antimonides: Low emittance ultrafast photocathodes", *Appl. Phys. Lett.*, vol. 101, p. 194103, 2012.

[6] K. Floettmann, ASTRA particle tracking code', `http://www.desy.de/~mpyflo/`.

[7] G. Asova *et al.*, "Investigations on the thermal emittance of Cs2Te photocathodes at PITZ", in *Proc. 29th Int. Free Electron Laser Conf. (FEL'07)*, Novosibirsk, Russia, Aug. 2007, paper WEPPH012, pp. 350–353.