Development of an Offline Measurement Apparatus for Photocathode Intrinsic Emittance

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Date: 2025-05-05T22:06:25+00:00

Abstract

The intrinsic emittance of photocathodes represents the lower limit of emittance achievable by photocathode electron source devices, and the development of low-intrinsic-emittance photocathodes is of great significance for advancing free-electron lasers, ultrafast electron diffraction, and similar facilities. Conventional measurement methods for photocathode intrinsic emittance rely on large-scale accelerator facilities, which is not conducive to rapid evaluation and process optimization of photocathode intrinsic emittance in laboratory environments. This paper presents the design and construction of an offline intrinsic emittance measurement device for photocathodes based on the free-space drift principle. The device is compatible with photocathode fabrication apparatus and supports offline measurement and characterization of the intrinsic emittance of fabricated photocathodes. Using this device, measurement and analysis of the quantum efficiency and intrinsic emittance of fabricated cesium telluride photocathodes were conducted, with the results being of significant importance for optimizing photocathode process parameters.

Full Text

Development of an Offline Measurement System for Photocathode Intrinsic Emittance

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Abstract

Photocathode intrinsic emittance represents the lower limit of emittance achievable by photocathode electron sources. Developing photocathodes with low intrinsic emittance is critical for advancing applications such as free-electron lasers and ultrafast electron diffraction. Conventional methods for measuring photocathode intrinsic emittance rely on large-scale accelerator facilities, which are unsuitable for rapid measurement and process optimization in laboratory environments.

This study aims to develop an offline intrinsic emittance measurement system for the optimization of photocathode process parameters. Based on the free-space drift principle, an intrinsic emittance measurement system was designed and constructed. The measurement principle used in this system was presented in detail. The system is compatible with photocathode preparation facilities, enabling offline characterization of the cesium telluride (Cs_2Te) photocathode prepared by the emittance. Using this system, photocathode preparation facility was measured and analyzed. The measurement results show that the intrinsic emittance of the cesium telluride (Cs_2Te) photocathode is 0.592 mm · mrad/mm, which is consistent with the measurement results of cesium telluride photocathodes reported. The measurement results of the intrinsic emittance under different bias voltages between the anode and the cathode are in good agreement with the theoretical values, indicating the reliability of the measurement results.

Keywords: photocathode, intrinsic emittance, electron source

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1. Background

For photocathode injectors, the photocathode serves as the electron beam source, and its performance directly determines the electron beam quality. Photocathode intrinsic emittance is a crucial physical parameter describing photocathode performance. It arises from the residual kinetic energy of photoelectrons after escaping the photocathode surface and is closely related to the photocoelectric properties, operating parameters, and surface roughness of the photocathode. Unlike contributions from space charge effects and other factors to beam emittance, the contribution from photocathode intrinsic emittance cannot be compensated or eliminated by downstream beamline elements. Therefore, photocathode intrinsic emittance represents the lower limit of electron beam emittance achievable in linear accelerator facilities. Measuring and optimizing photocathode intrinsic emittance is essential for improving beam quality.

Currently, various measurement methods have been developed internationally, such as momentum-space imaging, solenoid scanning, and "pepper-pot" techniques for photocathode intrinsic emittance measurement. However, these methods mostly rely on large-scale accelerator facilities, involve complex equipment, and are unsuitable for iterative photocathode preparation process optimization. Additionally, the measurement process is susceptible to space charge effects and beam optics influences. Furthermore, high-quantum-efficiency semiconductor photocathodes are chemically active and sensitive to gas components such as H_2O, O_2, and CO_2. These methods typically require additional transfer and loading devices to transport samples between preparation and accelerator facilities, which hinders rapid measurement and analysis during photocathode preparation.

This paper presents the design and construction of an offline intrinsic emittance measurement system based on the free-space drift principle, suitable for laboratory environments. The system features a photocathode transfer interface and enables transmission of photocathodes between preparation and measurement facilities under vacuum conditions, allowing for rapid offline measurement of photocathode intrinsic emittance. This provides an efficient and convenient solution for guiding photocathode process optimization and reducing intrinsic emittance.

2. Measurement Principle

[Figure 1: see original paper]

The layout of the photocathode intrinsic emittance measurement system is shown in Figure 1. Photoelectrons are emitted from the cathode, accelerated through the voltage between the cathode and anode, pass through the anode mesh region, drift through a field-free region of length d, and are finally detected by the detector. The entire device circuit applies negative voltage to the cathode, while the anode, detector, and chamber are grounded. When photoelectrons are emitted from the cathode and accelerated by the voltage between cathode and anode to reach the anode mesh, they undergo parabolic motion.

The position as a function of time can be derived from Newtonian mechanics as follows:

The cathode-anode voltage is V, the cathode-anode gap is g, z is the initial velocity along the longitudinal direction, e is the electron charge, m is the electron mass, and the flight time between cathode and anode is:

Based on equation (1), the flight time of photoelectrons in the cathode-anode region can be obtained. The initial electron kinetic energy in the longitudinal z direction is E_0. In photocathode electron source applications, the initial electron energy is typically less than 1 eV, while the cathode-anode voltage V in measurements is usually on the order of ~kV. Therefore, equation (2) can be simplified to:

Since there is no transverse electric field along the x direction, the transverse momentum of electrons can be given by equation (4):

where x is the transverse displacement of electrons when they reach the anode mesh. The angle between the z direction and x direction at the anode mesh can be given by equation (5):

The initial kinetic energy of electrons along the x direction. Combining equation (3), the transverse displacement x of electrons at the anode mesh can be given by:

The transverse displacement L produced by electrons traveling from the cathode to the detector can be given by (7):

According to the definition of photocathode intrinsic emittance (equation (8)), combining equations (5)–(7) allows determination of the photocathode intrinsic emittance based on measured transverse displacement and device parameters, as shown in equation (9):

where 핎 is the measured photocathode intrinsic emittance.

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3. System Design

3.1 Overall System Layout

Since high-quantum-efficiency semiconductor photocathodes are chemically active and sensitive to gas components such as H_2O, O_2, and CO_2, photocathode preparation and intrinsic emittance measurement must be conducted under ultra-high vacuum conditions (~10^{-8}–10^{-10} Pa). To achieve non-destructive transfer and measurement of photocathodes, the intrinsic emittance measurement device employs a compatible installation interface with the photocathode preparation facility. The overall layout of the offline intrinsic emittance measurement system is shown in Figure 2 [Figure 2: see original paper], consisting primarily of a measurement chamber, transfer chamber, and transition section.

The measurement chamber is used for intrinsic emittance measurement of photocathodes. The transfer chamber facilitates transport of photocathodes between the preparation facility and the emittance measurement system. The transition section ensures vacuum connection between the transfer chamber and measurement chamber. Photocathode transfer between the transfer chamber and measurement chamber is achieved using a magnetic manipulator and cathode cartridge.

[Figure 2: see original paper]

3.2 Measurement Chamber Design

The photocathode intrinsic emittance measurement chamber includes components for drive laser input/output windows, photocathode loading/unloading, cathode-anode assembly, and detection. The drive laser input/output windows enable laser injection and reflected light monitoring. The loading/unloading component provides functions for placing and removing cathode samples onto the cathode cartridge, installation and positioning, heating and cooling of the cathode substrate, and application of negative bias voltage. The mechanical design of this component is identical to that used in the photocathode preparation facility, ensuring sample transfer compatibility between the two systems. The cathode-anode assembly generates an electric field perpendicular to the photocathode surface to accelerate photoelectrons. The cathode-anode spacing uses 30 mm ceramic insulation, enabling voltage withstand greater than 10 kV. The minimum gap between cathode and anode is 5 mm. The cathode plate features a cathode aperture for inserting the cathode sample during measurement. To ensure field uniformity between cathode and anode and allow drive laser incidence on the cathode surface, the anode uses a 1 mm thick quartz plate with gold film coating for conductivity and light transmission. A 3 mm diameter aperture at the center of the anode accommodates the anode mesh, allowing the electron beam to pass through.

[Figure 3: see original paper]

To minimize measurement errors introduced by space charge forces, low-energy drive lasers are used to generate photoelectron beams for measurement. The detection component measures low-charge beam spot distributions using a microchannel plate (MCP) array combined with a phosphor screen. When photoelectrons drift to the detector, they first strike the MCP array for amplification before reaching the phosphor screen. The fluorescence produced by the phosphor screen is coupled through an optical system to a CCD (Charge Coupled Device) for imaging. The MCP used in the system has a maximum gain coefficient of 10^6. The phosphor screen has an electro-optical conversion efficiency of approximately 60% (20 ph/e/kV @ 3 kV).

3.3 Drive Laser System Design

Since cesium telluride photocathodes operate in the ultraviolet wavelength range, the measurement light source uses a 266 nm semiconductor laser. The drive laser layout is shown in Figure 4 [Figure 4: see original paper]. A UV attenuator installed at the laser output adjusts the laser power. To minimize measurement errors from drive laser spot size, the spot size on the cathode must be smaller than 100 m. The optical path employs a combination of aperture shaping and phase transfer techniques. A 100 m aperture shapes the transverse beam profile, followed by a single-lens imaging (phase transfer) scheme to transfer the spot at the aperture proportionally to the photocathode surface.

[Figure 4: see original paper]

To enable real-time measurement of the drive laser spot size on the photocathode, a virtual cathode optical path is constructed using beam splitting before the measurement chamber entrance window. Figure 5 [Figure 5: see original paper] shows the spot distribution measured on the virtual cathode using a CCD, yielding a spot size (FWHM, Full Width at Half Maximum) of ~100 m, consistent with the aperture diameter used.

[Figure 5: see original paper]

4. Experimental Results

The photocathodes used in the experiments were prepared using a Te-intermittent, Cs-continuous deposition process, which has been applied in hard X-ray free-electron laser facilities and high-current electron gun test platforms. Quantum efficiency and intrinsic emittance are two critical metrics for evaluating photocathode performance. Both parameters were measured and evaluated for laboratory-prepared cesium telluride (Cs_2Te) photocathodes using the offline intrinsic emittance measurement system.

4.1 Photocathode Quantum Efficiency Measurement

The photocathode transfer chamber is equipped with a quartz window and electrode interface, enabling quantum efficiency measurement. Before transfer to the measurement chamber, photocathode quantum efficiency distribution can be measured in the transfer chamber. The measurement optical path uses the same drive laser system as the emittance measurement (Figure 4), with a laser spot size (FWHM) of ~100 m on the cathode. An electric mirror mount measures quantum efficiency at different positions on the photocathode surface to map the quantum efficiency distribution. Figure 6 [Figure 6: see original paper] shows the measured quantum efficiency distribution with an incident wavelength of 266 nm. The photocathode diameter is ~7 mm, and the measured quantum efficiency at different positions exceeds 5%, reaching a maximum of ~12.5%, meeting the requirements for high-quantum-efficiency photocathode applications.

[Figure 6: see original paper]

4.2 Photocathode Intrinsic Emittance Measurement

After completing quantum efficiency measurement, the photocathode is transferred to the measurement chamber for intrinsic emittance measurement. Figure 7 [Figure 7: see original paper] shows the electron beam spot distribution measured on the CCD. In the measurement experiment, the drive laser power was ~100 nW, the cathode-anode bias voltage was 5 kV, the cathode-anode gap g was 5 mm, and the drift distance d was 270 mm. The measured electron beam spot size (FWHM) was 1.4 mm, yielding a photocathode intrinsic emittance of $0.592\ \text{mm} \cdot \text{mrad/mm}$ according to equation (9).

To verify measurement accuracy, electron beam spot sizes on the detector were measured under different cathode-anode bias voltages and compared with theoretical values. Figure 8 [Figure 8: see original paper] demonstrates good agreement between measured photocathode intrinsic emittance and theoretical values, confirming the reliability of the measurement results. Additionally, based on international investigations of cesium telluride photocathode intrinsic emittance, typical values range from $0.50\text{–}1.0\ \text{mm} \cdot \text{mrad/mm}$ (depending on drive laser wavelength, cathode gradient, and preparation process), which further validates the accuracy of our measurement results.

[Figure 7: see original paper]

To verify that space charge effects do not influence the photocathode intrinsic emittance measurement results, intrinsic emittance was measured under different drive laser powers, as shown in Figure 9 [Figure 9: see original paper]. The results indicate that intrinsic emittance remains essentially constant with varying laser power, demonstrating that space charge effects have no impact on the measurement results in these experiments.

[Figure 8: see original paper]

[Figure 9: see original paper]

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5. Conclusion

Photocathode intrinsic emittance fundamentally determines the ultimate quality of electron beams, and its measurement provides crucial guidance for optimizing photocathode process parameters. This paper presents the design and construction of an offline intrinsic emittance measurement system based on the free-space drift principle. The system enables non-destructive transfer of photocathodes between preparation and measurement facilities, supporting measurement of both quantum efficiency and intrinsic emittance. Using this system, we measured the quantum efficiency and intrinsic emittance of photocathodes prepared using the Te-intermittent, Cs-continuous deposition process. The measurement results agree well with theoretical predictions and are consistent with internationally reported values for cesium telluride photocathodes. Future work will focus on analyzing factors influencing photocathode intrinsic emittance and optimizing the photocathode preparation process using this system to support the development of photocathodes with even lower intrinsic emittance.

Author Contributions

FENG Zhiwen was responsible for optical path construction and debugging, intrinsic emittance measurement, and manuscript writing. LI Xudong handled photocathode preparation, transfer, and transport. MENG Hao conducted intrinsic emittance measurements. ZHOU Qin performed photocathode preparation. HOU Tao collected experimental data. JIANG Zenggong designed the intrinsic emittance measurement system, designed experiments, performed system debugging, and contributed to manuscript writing. GU Qiang designed experiments, provided guidance, and assisted with manuscript revision.

Acknowledgements

This work was partially supported by the National Natural Science Foundation of China (Grant No. 12275339, No. 12075302), Science and Technology Innovation Plan of Shanghai Municipal Committee of Science and Technology (22ZR1470300), and the Youth Innovation Promotion Association of Chinese Academy of Sciences (2023300).

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Note: Figure translations are in progress. See original paper for figures.