

MTE MEASUREMENTS AT THE ASU CRYOGENICALLY COOLED DC ELECTRON GUN

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Abstract

The ASU cryogenically cooled DC electron gun represents a state-of-the-art platform for testing novel photocathodes at room and cryogenic temperatures. The key electron beam diagnostic tool of this setup is the four-dimensional (4D) phase space reconstruction using the pinhole scan technique. In this work, we use the 4D phase space measurement to extract the Mean Transverse Energy (MTE) obtained from cathodes in this gun. We also establish the limits and accuracy of the 4D phase space and emission area measurements and estimate their effects on the MTE extracted. The results, validated through simulations and complementary measurements, establish the use of the 4D phase space measurement technique to obtain the MTE. Using this approach, we measure the MTE from alkali antimonide photocathodes at varying temperature and electric field conditions. This study provides a robust foundation for future experiments with the ASU electron gun and beamline, paving the way for advanced photocathode characterization under cryogenic conditions.

INTRODUCTION

High-brightness electron beams are essential for advanced scientific applications such as X-ray Free Electron Lasers (XFELs) [1, 2], Ultrafast Electron Diffraction (UED) [3], and Ultrafast Electron Microscopy (UEM) [4]. The beam brightness is inversely proportional to the transverse emittance, which is determined by the mean transverse energy (MTE) of photoemitted electrons [5]. At the cathode, the normalized RMS emittance is given by:

$$\varepsilon_{n,x} = \sigma_x \sqrt{\frac{\text{MTE}}{mc^2}}, \quad (1)$$

where: $\varepsilon_{n,x}$ is the normalized transverse emittance in the x direction, σ_x is the RMS laser spot size in the x direction, m is the rest mass of the electron, c is the speed of light, and MTE is the mean transverse energy.

MTE depends on factors such as photocathode material, laser photon energy, and surface conditions. A key parameter is the excess energy $E_{\text{excess}} = h\nu - \phi$, which contributes to transverse momentum. Assuming a constant density of states near the Fermi level and no scattering during the transport of excited electrons toward the cathode surface prior to emission the MTE can be related to excess energy as $\text{MTE} = E_{\text{excess}}/3$ [6]. Near-threshold photoemission minimizes excess energy, leading to emission primarily from the Fermi tail, with a lower bound of:

$$\text{MTE} \approx k_B T, \quad (2)$$

where: k_B is the Boltzmann constant, and T is the lattice temperature [7].

While reducing excess energy lowers MTE, it often compromises QE. Lower QE requires larger laser fluence to achieve the same charge density. Larger laser fluence can increase the probability of non-linear photoemission leading to higher MTE [8]. Alkali-antimonide photocathodes mitigate this tradeoff by maintaining high QE at low excess energy [9] making them suitable for high-brightness photoinjectors. Although theory predicts reduced MTE near threshold, comprehensive experimental validation across multiple wavelengths at room and cryogenic temperatures has been lacking.

The cryogenically cooled ASU DC electron gun [10] provides an excellent platform to test these photocathodes at cryogenic temperatures. In this work, we report MTE values at four photon energies and show a notable reduction at 532 nm when cooled to 50 K, revealing new insights into photoemission behavior under cryogenic conditions.

MTE MEASUREMENT SETUP

The MTE was derived from Eq. (1) by obtaining the emittance in the beamline connected to the DC gun and the size of the laser spot on the cathode. The laser spot size was measured using a beam profile monitor situated at a distance equal to the distance of the cathode from the final focusing optic.

The emittance was obtained using a 4D phase-space reconstruction via the pinhole scan technique [11, 12]. The pinhole scan technique measures the beam profile after passing the beam through a small pinhole followed by a drift space. Scanning the beam over the pinhole selects a certain transverse position (x, y) in the beam. The image recorded after the pinhole and drift is a direct measure of the transverse momenta (p_x, p_y) at that particular transverse position in the beam giving the complete 4D phase space. The transverse momentum in the x and y directions are obtained using the projections of this 4-D phase space.

The beam is scanned over the pinhole using a single steering dipole magnet in each transverse direction. The momentum introduced by the steering dipole magnet is subtracted during the processing of the images. The beam was focused on the pinhole to minimize the momentum kick introduced by the steering magnet. If this kick is much larger than the momenta in the beam, small relative errors in the momentum kick that is subtracted result in large relative errors in the calculated momenta, giving an inaccurate phase space and

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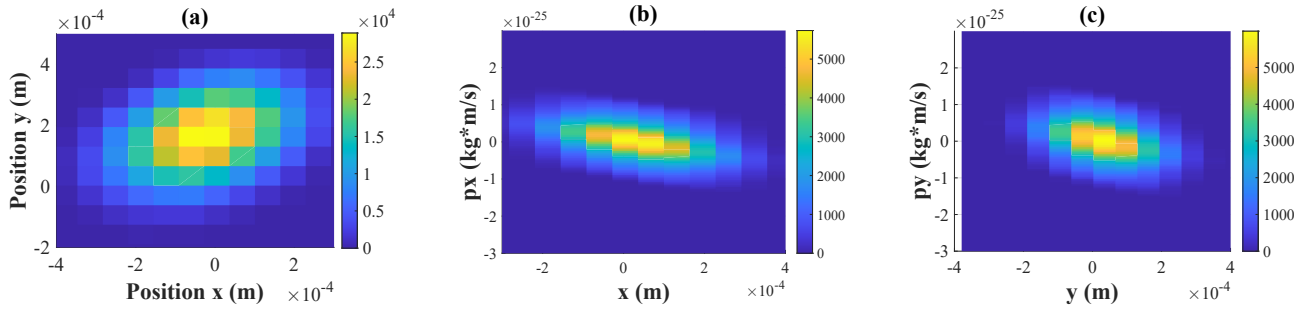


Figure 1: Room Temperature Phase Space Plots at 532 nm. (a) Spatial phase space distribution in the transverse x-y plane; (b) Phase space correlation between x - p_x ; (c) Phase space correlation between y - p_y .

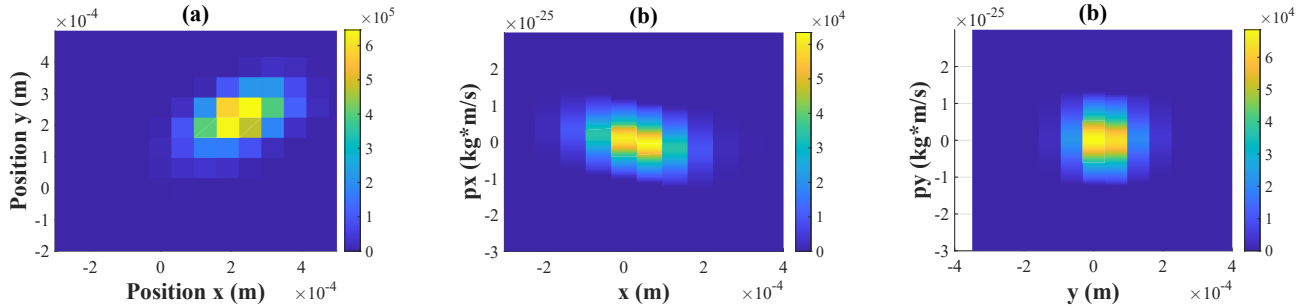


Figure 2: Phase space plots at 532 nm with the cathode at 50 K. (a) Spatial phase space distribution in the transverse x-y plane; (b) Phase space correlation between x - p_x ; (c) Phase space correlation between y - p_y . The cryogenic phase space plots show a dramatic reduction in phase space volume that is also reflected in the emittance.

emittance. Additionally, a small aspect ratio of the diameter to thickness of the pinhole can cause the pinhole to introduce aberrations in the beam when passing through it. Here, a 30 μ m diameter pinhole with a thickness of 100 μ m was used.

Figures 1 and 2 show the various projections of the measured 4D phase space for the beam generated from a Cs₃Sb photocathode using the 532 nm wavelength at room and cryogenic (50 K) temperature, respectively. The MTE derived from the emittance and laser spot size measurements in this work is consistent, within experimental uncertainties, with the MTE values reported by Kachwala *et al.* [9], who utilized a Photoemission Electron Microscope to measure MTE for Cs₃Sb photocathodes deposited on a silicon substrate.

MTE RESULTS

A Cs₃Sb photocathode was grown, on a Si substrate, in the ASU growth chamber and then transferred to the electron gun via a UHV transfer line [13]. MTE values were measured for four different photon wavelengths: 532 nm, 635 nm, 650 nm, and 670 nm (see Fig. 3). For measurements at cryogenic temperatures the cathode plug was inserted into the gun after cooling the gun electrodes. The photocathode maintained a high quantum efficiency (QE) across the various wavelengths, achieving a QE of 3% at 532 nm, 0.05% at 635 nm, 0.025% at 650 nm, and 0.017% at 670 nm at 50 K. After cooling the cathode to 50 K, MTE measurements were taken at the same photon wavelengths.

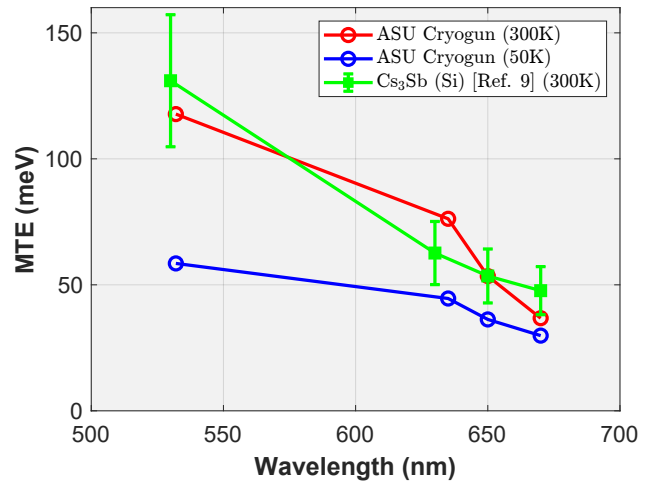


Figure 3: MTE as a function of incident laser wavelength for Cs₃Sb photocathode under different conditions. Measurements were performed using the ASU cryogun at room temperature (300 K, red circles) and at cryogenic temperature (50 K, blue circles). These results are compared with MTE values reported in Ref. [9] (green squares) for Cs₃Sb deposited on a silicon substrate, measured using a Photoemission Electron Microscope at 300 K.

CONCLUSION AND FUTURE WORK

This work uses 4D phase space measurements to reliably capture the MTE of electrons from Cs₃Sb photocathodes, showing clear reductions with lower photon energy and cryo-

genic cooling. Building on these results, we will next perform a comprehensive QE study at both room and cryogenic temperatures under different cooling methods, aiming to understand how different cooling procedures impact QE and identify strategies to maintain high QE during cryogenic operation.

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