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PERFORMANCE CHARACTERISATION OF A Cu (100) SINGLE–CRYSTAL PHOTOCATHODE

L. A. J. Soomary[1*], D. P. Juarez–Lopez[1], C. P. Welsch[1]
Department of Physics, University of Liverpool, United Kingdom
L. B. Jones[2], T. C. Q. Noakes[2], The Cockcroft Institute, Warrington, United Kingdom
[1]also at The Cockcroft Institute, Warrington, United Kingdom
[2]also at ASTeC[†], STFC Daresbury Laboratory, Warrington, United Kingdom

Abstract

The search for high performance photocathode electron sources is a priority in the accelerator science community. The surface characteristics of a photocathode define important factors of the photoemission including the intrinsic emittance, the quantum efficiency and the work function of the photocathode. These factors in turn define the electron beam performance which are measurable as emittance, brightness and energy spread.

ASTeC's Multiprobe (SAPI) [1] system has been used to characterise and analyse photocathode performance using multiple techniques including XPS, STM, and LEED imaging, and their Transverse Energy Spread Spectrometer (TESS) [2] to measure mean transverse energy (MTE).

Characterisation measurements will be presented for a Cu (100) single–crystal photocathode sample, with data from SAPI confirming the crystallographic face and showing surface composition and roughness, supported by data from TESS showing the photocathode electron beam energy spread.

INTRODUCTION

Intrinsic emittance defines the lowest achievable limit of emittance in a well–configured linear accelerator, and in the absence of space charge, the source emittance can be preserved throughout acceleration in machines of this class [3]. Many different factors directly affect the photocathode intrinsic emittance, such as composition, crystallographic structure, surface roughness, cleanliness, work function and quantum efficiency (QE), and these combine to affect the overall beam emittance.

Reducing the intrinsic photocathode emittance impact directly the cost of a Free–Electron Laser (FEL) facility driven by such an accelerator as peak electron beam brightness can be achieved in a smaller facility while also increasing the X–ray beam brightness and hence the machine performance [4].

Polycrystalline metal photocathodes (typically copper) are used as electron sources in accelerators due primarily to their robustness and response time, but ultimately these electron sources are performance limited by their transverse and longitudinal energy spread. The ability to measure the Mean Transverse Energy (MTE) of the photoelectrons emitted from the cathode is a key performance parameter in order to improve the accelerator beam quality as the maximum possible brightness is directly proportional to the nth power of the accelerating electric field but is inversely proportional to the MTE of the emitted electrons. For this reason, understanding and managing the mechanisms and processes which affect the MTE is crucial for obtaining brighter electron beams with minimal MTE.

In this paper, we will present data showing the progressive change in MTEs extracted from energy distribution curves measured for electrons emitted from a copper (100) single–crystal as a function of the illumination wavelength at both room and cryogenic temperature. In addition, we will present an in–depth study for photoemission close to the emission energy threshold at both temperatures.

EXPERIMENTAL DETAILS

A single–crystal copper sample was sourced from Surface Preparation Laboratory B.V., cut to expose the (100) face and polished to a surface roughness of $R_a < 30$ nm. The cathode was prepared and cleaned in the Multiprobe system [1] by performing repeated argon ion bombardment and thermal annealing cycles until no oxygen or carbon contamination signatures were present in the XPS survey spectra. Once clean, the surface roughness was verified using in–vacuum STM, and the crystallographic face confirmed using LEED.

The sample was then moved into our Photocathode Preparation Facility (PPF) using a vacuum suitcase which maintained a pressure in the low 10^{-10} mbar region during the transfer. The cathode was stored in the PPF until required, and was thermally cleaned to 823 K (550 °C) immediately before its transfer into the TESS for MTE measurements. The TESS system typically maintains a chamber pressure around 3×10^{-11} mbar.

In this work, data was taken using 3 accelerating fields based on potential differences between the photocathode source and electron detector of 150, 100 and 60 V. The TESS detector and principle of operation is described in detail by Jones *et al.* [2]. The Micro Channel Plate (MCP) back plate voltage was adjusted over the range + 900 to + 1275 V, dependent on the photocathode illumination wavelength, and the phosphor screen was typically held at + 4 kV throughout. All photoemission measurements were made under the same room lighting conditions, i.e., with as much ambient light removed as possible through the use of a laser curtain around the TESS experiment. The electron emission foot-

* liam.soomary@cockcroft.ac.uk
† ASTeC: Accelerator Science and Technology Centre

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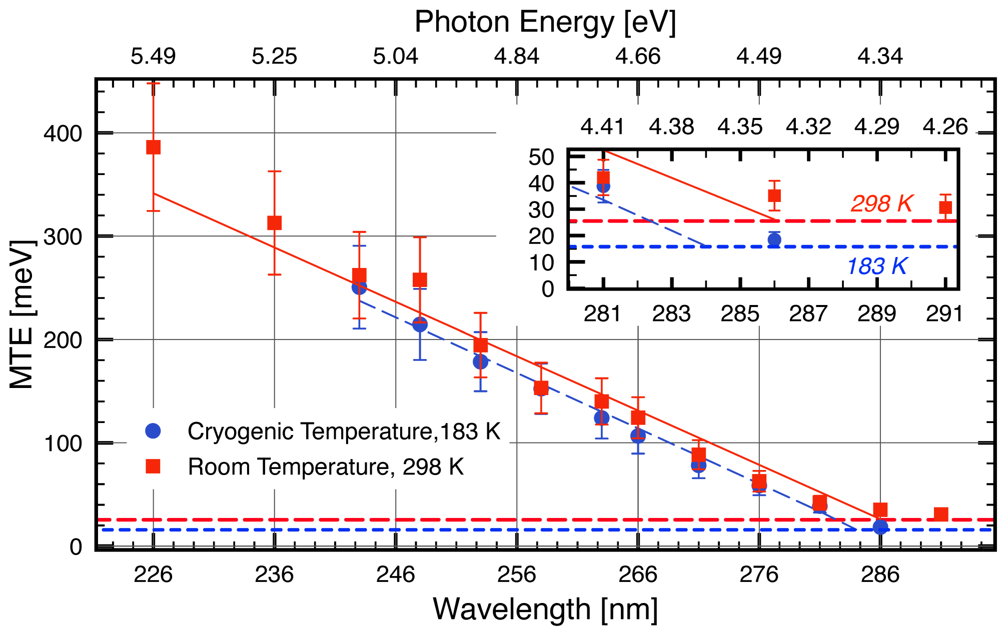

Figure 1: MTE values for a copper (100) single–crystal cathode at two different temperatures. The MTE lower threshold defined by k_BT is shown by the red and blue horizontal dotted lines for $T = 298$ and 183 K respectively, with the inset showing the detail close to the photoemission threshold.

print images produced on the phosphor screen were recorded using a camera exposure time of 100 s for each illumination wavelength, with the same camera exposure and detector voltages used for the corresponding 'dark' image.

EXPERIMENTAL RESULTS

Transverse Energy Distribution Curves (TEDCs) were measured for each illumination wavelength, with an exponential curve fitted to each TEDC as described in [5] to determine the MTE at each wavelength.

Figure 1 shows the MTE measurements as a function of the illumination wavelength. The red squares show the MTE values measured at room temperature (298 K), and the blue circles those at cryogenic temperature (183 K). The chain–dotted lines denote the minimum achievable MTE defined by k_BT where k_B is the Boltzmann constant (1.381×10^{-23} JK^{-1}) and T is the lattice temperature in Kelvin.

The data shows the direct dependence of MTE on the illumination wavelength at high photon energies away from the photoemission energy threshold, with high values of MTE obtained for short illumination wavelengths, and a progressive decrease in the MTE as the wavelength is increased. This relationship is based on the excess energy (ε) during photoemission which is the difference between the surface work function (ϕ) and the illuminating photon energy ($h\omega$):

$$\varepsilon = \phi - h\omega = \phi - \left(\frac{hc}{e} \cdot \frac{1}{\lambda}\right)$$

and it can be seen that MTE varies inversely to λ. The minimum value of MTE which is set by the crystal lattice temperature (k_BT) is reached as the illumination wavelength approaches the photoemission energy threshold, and it can be seen that the linear dependence breaks down at this point.

Cu(100) at the Photoemission Energy Threshold

Motivated by the recently published studies from the Arizona State University using a high–resolution 3D time–of–flight electron energy analyser [6, 7] where a record low mean transverse energy of 5 meV was measured near the photoemission threshold from a copper (100) surface cooled using liquid helium to 35 K, we took a further set of measurements with the TESS focussing on behaviour close to the photoemission energy threshold. The experimental conditions for these additional measurements were the same as for both previous sets of measurements with the TESS.

Figure 2 shows our MTE measurements close to the energy threshold as the illumination wavelength was progressively changed over the range 271 – 289 nm in 2 nm steps. Room temperature measurements at 294 K are shown by the black squares, and the blue circles denote measurements taken in a temperature range from 173 – 183 K. A summary of the MTE values over this range can be found in Table 1.

The lowest MTE of 16.7 meV was measured under illumination at 289 nm with the photocathode cooled to 178 K where the lower thermal emission energy limit is $k_BT = 15.8$ meV. This last measurement was not easy to take as the quantum efficiency at this wavelength was extremely low and the photon energy was barely enough to overcome the work function. This was compensated to some extent through an increase in the MCP gain with a corre-

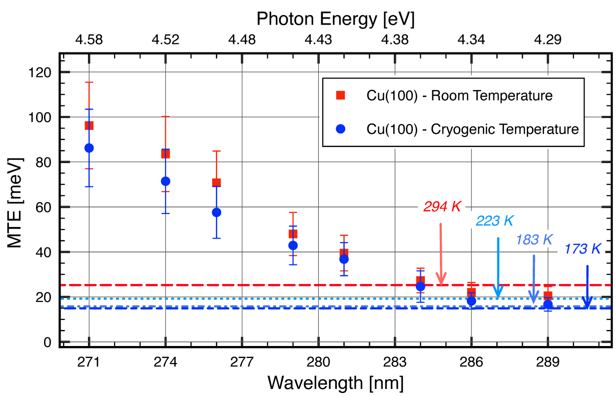

Figure 2: MTE values for a single crystal Copper (100) cathode at two different temperatures. The lower energy limit at different temperatures is shown by dotted lines.

Table 1: MTE Values for a Cu (100) Photocathode Close to the Photoemission Energy Threshold

Wavelength [nm]	**MTE [meV] at 294 K**	**MTE [meV] at 178 K**
271	96.2	86.2
274	83.5	71.4
276	70.7	57.6
279	48.0	42.9
281	39.5	42.9
284	27.3	24.6
286	22.0	18.2
289	20.5	16.7

sponding intensity increase at the phosphor screen, and an increase in the camera exposure time.

CONCLUSIONS

We have measured the photoemission footprint of electrons photoemitted from copper (100) single–crystal surfaces at a range of different illumination photon energies and demonstrated both a linear relationship in MTE as a function of illumination wavelength and the MTE lower limit which is set by the photocathode temperature.

This work has been possible largely due to recent upgrades to the TESS system leading to improved performance of the light source and increased detector sensitivity. When combined, these upgrades confer the ability to work very close to the photoemission threshold, and have allowed us to record the lowest MTE measured to–date using the TESS of of 16.7 meV.

These detailed measurements highlight a crucial aspect of photoemission physics close to the photoemission energy threshold where very low MTEs are achievable, but where the linear relationship between illumination wavelength and MTE appears to break down, and also that photoemission is possible and measurable at illumination photon energies which are less than the accepted work function. The ability to generate electron beams with such low energy spread demonstrates significant advances towards increasing electron beam brightness for ultra–fast electron scattering and XFEL applications.

FURTHER WORK

Recognising that single–crystal metals are not generally used as photocathode electron sources, and building on work instigated to study the effects of the progressive degradation of a clean photocathode surface which simulate the environment in which photocathodes typically operate in a vacuum system, we hope to repeat detailed MTE measurements for a polycrystalline copper sample following broadly similar experimental procedure as that described in our work relating to the degradation of silver as a photocathode (see paper WEPAB111 in these proceedings [8]).

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