

THE EVOLUTION OF THE TRANSVERSE ENERGY DISTRIBUTION OF ELECTRONS FROM A GaAs PHOTOCATHODE AS A FUNCTION OF ITS DEGRADATION STATE

L.B. Jones*, B.L. Militsyn, T.C.Q. Noakes

STFC Daresbury Laboratory, ASTeC & the Cockcroft Institute, Warrington WA4 4AD, UK

H.E. Scheibler, A.S. Terekhov

Institute of Semiconductor Physics (ISP), SB RAS, Novosibirsk 630090, Russia

Abstract

The brightness of a photoelectron injector is fundamentally limited by the mean longitudinal and transverse energy distributions of the photoelectrons emitted from its photocathode, and is increased significantly if the mean values of these quantities are reduced. To address this, ASTeC constructed a Transverse Energy Spread Spectrometer (TESS) [1] – an experimental facility designed to measure these transverse and longitudinal energy distributions which can be used for III-V semiconductor, alkali antimonide/telluride and metal photocathode research. We present measurements showing evolution of the transverse energy distribution of electrons from GaAs photocathodes as a function of their degradation state. Photocathodes were activated to negative electron affinity in our photocathode preparation facility (PPF) [2,3] with quantum efficiency around 10.5%. They were then transferred to TESS under XHV conditions, and progressively degraded through controlled exposure to oxygen. Data has been collected under photocathode illumination at 635 nm, and demonstrates a constant relationship between energy distribution and the level of electron affinity.

INTRODUCTION

The development of high-performance accelerator drivers for Free-Electron Laser facilities requires electron source technology which delivers a high-brightness electron beam for reasons that are well-documented [4]. Electron beam brightness in a linear accelerator is fundamentally limited by injector brightness, and this is itself limited by the source beam emittance or the *intrinsic emittance* of the cathode source. Electron beam brightness will be increased significantly by reducing the longitudinal and transverse energy spread in the emitted electrons, thereby creating a *cold beam*. To accomplish this goal, we must understand the mechanisms which define the intrinsic emittance whether these are related to the properties external to the photocathode such as surface roughness and preparation methods, or properties internal to the photocathode such as purity, doping level, crystal structure, band structure etc. Consequently, the study of photocathode physics and electron emission have become important areas for research by the worldwide accelerator community.

* lee.jones@stfc.ac.uk

TRANSVERSE ENERGY MEASUREMENT

To measure the transverse energy using TESS, a photocathode is illuminated with a tightly-focussed laser beam typically 100 μm FWHM in diameter at extremely low intensity, and its emission footprint recorded at some known distance from the photocathode surface. Assuming a vanishingly-small source size, and knowing the drift distance travelled by the photoelectrons, and the effective voltage through which they have been accelerated (defining their flight time), the transverse energy component required to generate the observed emission footprint can be determined.

On emission from a photocathode, the transverse energy of a photoelectron is a convolution of the component of the electron momentum parallel to the cathode surface immediately prior to emission and the effects of surface diffraction during the emission process. It is measurable as the beam emittance at some distance from the source, and data from the TESS place an upper limit on the mean transverse energy (MTE). Measurement of the angular distribution of photoelectrons from a surface is very difficult due to the necessity to work with extremely low-energy electrons which can be potentially mis-steered through exposure to stray electric and magnetic fields. Even the application of angle-resolved photoelectron spectroscopy to measure this angular distribution is challenging as the angular distribution is affected by the specific geometry of the vacuum chamber and experiment itself, so measurements will vary in each installation. In the case of GaAs, published work indicates that the emission cone is narrow with a half-angle of only 15° [5].

For GaAs photocathodes, the upper limit on transverse electron energy is determined primarily by three factors, these being the illumination wavelength, the level of electron affinity and the photocathode temperature. The profile of the measured transverse energy distribution curve (TEDC) itself depends on various elastic and inelastic electron scattering processes at the photocathode-vacuum interface, which are themselves dependent on a number of factors such as surface roughness, surface diffraction, material structure/crystallinity etc.

The TESS system provides the ability to measure this transverse energy, and to make direct comparisons between photocathodes which have been prepared in different ways or experienced different conditions during operation. This

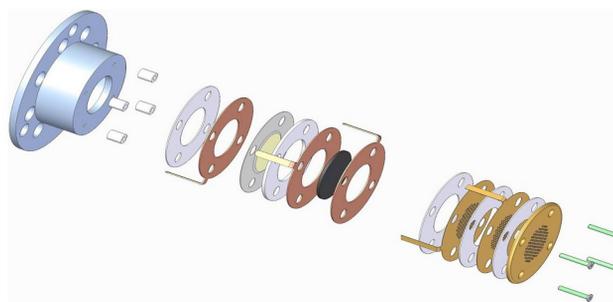
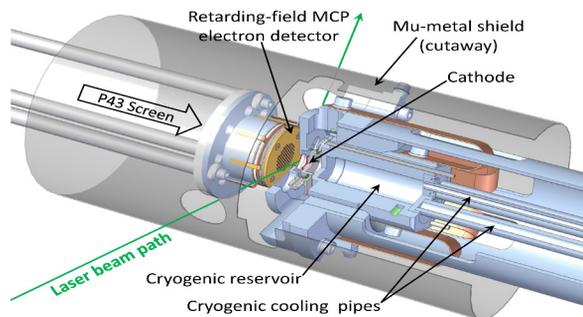


Figure 1: Detail of the TESS experimental system. **Left:** Overview with the vacuum chamber removed and the mu-metal magnetic shield and cathode holder cut away to aid clarity. The cathode holder is shown to the right, the detector to the left. **Right:** Schematic showing an exploded view of the retarding-field analyser and electron detector.

equipment is therefore a key enabling step towards increasing electron beam brightness for future accelerator facilities.

EXPERIMENT DESCRIPTION

The TESS system shown in Fig. 1 combines a reflection-mode photocathode holder under grazing-incidence illumination with a retarding-field analyser and electron detector and imaging system. The photocathode holder can be electrically biased, and can also be cryogenically-cooled to liquid nitrogen temperature. The source and detector have been designed to be symmetric and flat, and contain only non-magnetic components. The addition of a mu-metal shield around the source and detector screen against external magnetic fields. A full description of the instrument can be found in a previous publication [6].

Experiments were performed on p^+ -GaAs(100) photocathodes supplied by the ISP and activated in the PPF following established procedures [7, 8], achieving about 10 % quantum efficiency (Q.E.) at 635 nm. Once loaded into TESS, photocathodes were illuminated with CW laser light at a wavelength of 635 nm. Prior to measurements, the laser power delivered to the cathode was adjusted using ND filters to establish a measurable drain current from the photocathode of around 10 pA. During measurements, additional ND filters were inserted increasing beam attenuation by 10^4 pushing the extracted current to the 1 fA regime, thereby avoiding space-charge effects in the measurement.

Data was taken with the source biased at -15.5 V using a battery box. The detector grids and the MCP front plate were all held at +15.5 V, resulting in an overall accelerating potential (U_{acc}) of 31 V which defines the electron time of flight (τ). Application of the same potential to each of the detector grids and the MCP front plate ensured a constant-field region within the detector with no further acceleration.

The MCP back plate was held at +900 V, and the phosphor screen at +3.5 kV. Screen images showing the electron emission footprint were acquired using progressively-increasing camera exposure times, starting at 30 s, and increasing by a factor of 1.03 for each data image. All extraneous light was removed from around the experimental system as far as possible. Electron emission and dark background images

were taken in each case, and the dark image then subtracted to create a true image of the emission footprint. Fig. 2 shows typical beam emission footprints for a GaAs photocathode under illumination at $\lambda = 635$ nm.

Photocathodes were progressively degraded by exposure to oxygen admitted to the vacuum chamber at a very low partial pressure (typically 10^{-10} mbar) via a piezo-electric leak valve. Having noted the base pressure at the start of the experiment prior to oxygen admission, the chamber pressure was monitored constantly during data acquisition to express the time-integrated exposure in Langmuirs (L).

Data Analysis

With the background image subtracted, X- and Y- histograms of the true image were generated which summed each row and column in the data set. Analysis of the histograms was then applied to establish the image centroid, and a radial distribution function $I(r)$ was derived. The function $I(r)$ reflects the number of electrons incident in the annulus with radius r and thickness δr , with the radial displacement r of an electron from the image centroid (where $r = 0$) being dependent on its transverse energy ϵ_{tr} .

The drift distance between the source and the detector was 43 mm, and the longitudinal accelerating potential used was $U_{acc} = 31$ V. In all cases, $e \cdot U_{acc} \gg \epsilon_{lon}$, so the effect of longitudinal energy content at the instant of emission can

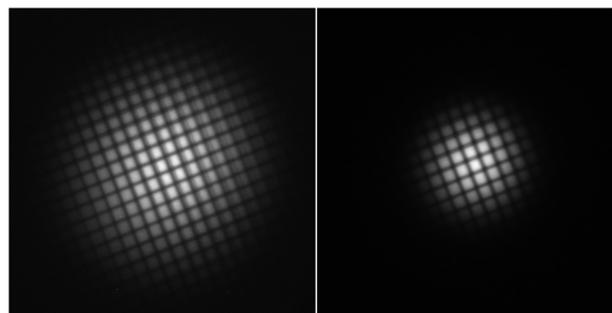


Figure 2: Typical electron emission footprints for GaAs under illumination at $\lambda = 635$ nm with the detector retarding grid structure super-imposed for $U_{acc} = 60$ V (left); and $U_{acc} = 230$ V (right).

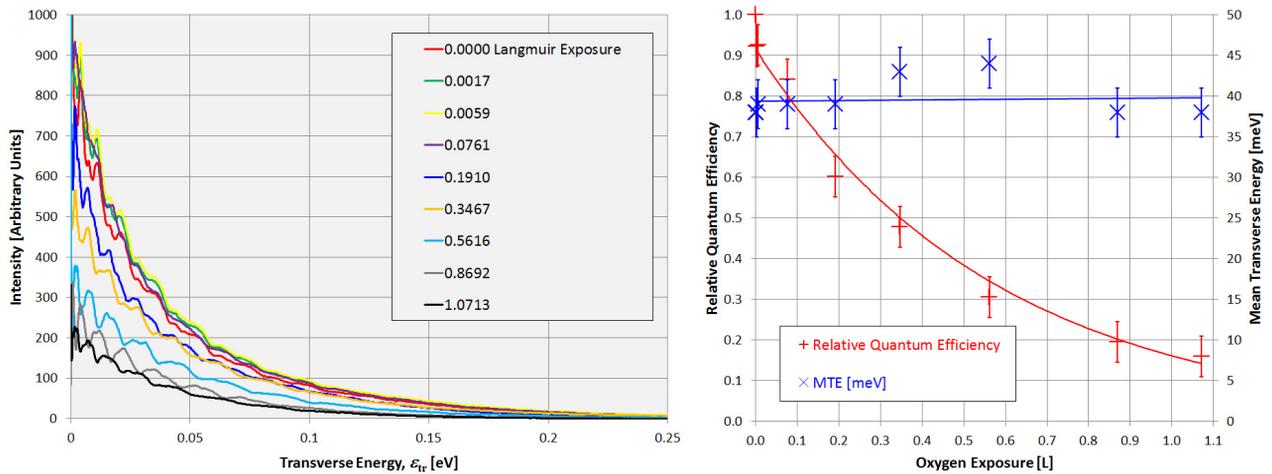


Figure 3: **(left)** Intensity distribution, $N(\epsilon_{tr})$, for photoelectrons emitted from GaAs under illumination by red laser light at 635 nm; **(right)** Normalised total signal intensity and fitted Mean Transverse Energies, ϵ_{tr} , measured during degradation.

be ignored as this will have a negligible effect on the overall flight time. TEDCs were calculated by converting the radial distribution function $I(r)$ to an energy distribution function $N(\epsilon_{tr})$ based on the radial displacement from the central emission point and the calculated flight time τ between the source and detector. The MTE was extracted by fitting an exponential curve of the form $\exp(-\frac{E}{MTE})$ to each of the $N(\epsilon_{tr})$ distribution functions measured for a particular level of photocathode degradation.

Results

The data shows that for the photocathodes studied which were activated to Q.E.s up to around 10.5 %, the magnitude of the transverse energy component ϵ_{tr} remains effectively constant, irrespective of the photocathode degradation state. The non-normalised data shown in Fig. 3 also shows the progressive reduction in electron emission and therefore image intensity which takes place as the photocathode under study is degraded through exposure to oxygen. After exposure to just over 1 L of oxygen, the cathode is severely degraded. Although Q.E. cannot be measured directly in the TESS instrument at present, estimates of the actual Q.E. associated with each dataset can only be derived from the electron emission intensity seen in the spectrometer images. Consequently, the Q.E. during the final measurement is estimated to be around 1.5 %.

Exponential curves of the form $y = A \times \exp(-\frac{\epsilon_{tr}}{B})$ where A is the peak intensity and B is the MTE at the $\frac{1}{e}$ level were fitted to the TEDCs shown in Fig. 3. Table 1 summarises

the MTEs extracted as a function of oxygen exposure. The measurements indicate that for the photocathodes tested, the MTE under illumination at 635 nm is 41 ± 3 meV for all levels of Q.E. from 10 % down to approximately 1.5 %. This agrees well with previously published data [1, 9, 10].

FUTURE WORK

A theoretical model of the TESS has been developed by the University of Liverpool [11], and its predictions will be compared to experimental data. The model will also be used to explore the effects of angular source distribution and field inhomogeneity on the measured results.

We will also investigate the effects of surface roughening and poor cathode preparation on MTE.

A vacuum suitcase is currently under construction. This will permit characterisation of metal photocathodes at room and cryogenic temperatures in TESS, while also giving access to AFM, SEM, XPS and LEED to study photocathode surfaces in detail. The vacuum suitcase will also be used to transport multi-alkali photocathodes from CERN for characterisation with the TESS.

Table 1: Summary of the MTEs Fitted to the TEDC Data

O ₂ Exposure [L]	0.0000	0.0017	0.0059	0.0761	0.1910	0.3467	0.5616	0.8692	1.0713
MTE [eV]	0.038	0.038	0.039	0.039	0.039	0.043	0.044	0.038	0.038

REFERENCES

- [1] L.B. Jones, K.J. Middleman, B.L. Militsyn, T.C.Q. Noakes, D.V. Gorshkov, H.E. Scheibler & A.S. Terekhov, Proc. FEL2013, TUPS033, 290-293
- [2] B.L. Militsyn, I. Burrows, R.J. Cash, B.D. Fell, L.B. Jones, J.W. McKenzie, K.J. Middleman, H.E. Scheibler & A.S. Terekhov, IPAC'10, TUPE095, pages 2347-2349
- [3] L.B. Jones, R.J. Cash, N. Chanlek, B.D. Fell, J.W. McKenzie, K.J. Middleman & B.L. Militsyn; Proc. IPAC '11, 3185-87
- [4] D.H. Dowell, I.V. Bazarov, B.M. Dunham, K.Harkay, C. Hernandez-Garcia, R. Legg, H. Padmore, T. Rao, J. Smedley & W. Wan; NIM 'A' 622 (2010), 685-697
- [5] Z. Liu, Y. Sun, P. Pianetta & R.F.W. Pease; J. Vac. Sci. Technol. B 23(6), 2005, 2758-2762
- [6] L.B. Jones, B.L. Militsyn, T.C.Q. Noakes, H.E. Scheibler & A.S. Terekhov; Proc. IPAC'14, MOPRI046, 707-710
- [7] W.E. Spicer & R.L. Bell; Pub. Astron. Soc. **84** 110 (1972)
- [8] W.E. Spicer, Appl. Phys. **12**, 115 (1977)
- [9] I.V. Bazarov, B.M. Dunham, F. Hannon, Y. Li, X. Liu, T. Miyajima, D.G. Ouzounov & C.K. Sinclair; Proc. PAC'07, 1221-1223
- [10] S. Matsuba, Y. Honda, X. Jin, T. Miyajima, M. Yamamoto, T. Uchiyama, M. Kuwahara & Y. Takeda; Jap. J. Appl. Phys. 51 (2012), 046402
- [11] L.J. Devlin, O. Karamyshev, C.P. Welsch, L.B. Jones, B.L. Militsyn & T.C.Q. Noakes; IPAC '14, MOPRI051, 720-723