GALLIUM ARSENIDE PHOTOCATHODE RESEARCH AT DARESBURY LABORATORY

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Abstract

Significant effort has been expended over several years by ASTeC to develop and optimise procedures for preparing GaAs photocathodes for use as high–current electron sources in accelerators. We present data showing high levels of Quantum Efficiency (*Q.E.*) for heterostructure photocathodes when activated with Cs-O and Cs-NF$_3$ procedures, and that the use of NF$_3$ delivers higher *Q.E.*, and conveys greater control during activation in that the final *Q.E.* level can be set more accurately when using NF$_3$.

A limiting factor in the performance of electron accelerators is the transverse energy spread in the photocathode source. We are designing a retarding–field electron calorimeter for the measurement of photoemission current as a function of retarding voltage. From this, we will establish the 2–D energy distribution of the emitted electrons, permitting a comparison of these figures for photocathodes at room temperature and at cryogenic temperatures. The goal is to investigate the possibility of creating an ultra–bright electron source based on GaAs technology.

INTRODUCTION

The ALICE[1] ERL at Daresbury Laboratory utilises a DC photoinjector electron gun, based on a Cs:GaAs photocathode, soldered inside the gun vacuum vessel. Its replacement is extremely time–consuming, with a high level of risk attached to the process. Preparation of the cathode takes place *in–situ*, with the cathode first heat–cleaned inside the photoinjector gun, then activated prior to use by exposure to caesium and an oxidant (typically oxygen or nitrogen tri–fluoride, NF$_3$) following established procedures [1, 2]. The cathode cleaning process exposes the conditioned high voltage (HV) electrodes to a variety of contaminants adsorbed onto the cathode wafer surface, and the activation process exposes the HV surfaces to caesium vapour and oxidant at a relatively high partial pressure, of which the caesium can be particularly damaging. Excessive use of caesium lowers the work function of the HV electrodes leading to field emission, and can cause HV breakdown during photoinjector operation.

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[1]Accelerators and Lasers In Combined Experiments

A Photocathode Preparation Facility

A solution to this problem has been the construction of an external photocathode preparation facility (PPF) with a load–lock interface to the photoinjector gun to separate the mutually–incompatible processes of cathode activation and photoinjector operation. The ALICE PPF has been constructed and commissioned in collaboration with the Novosibirsk Institute of Semiconductor Physics (ISP) [3], but due to the postponement of its installation on ALICE, the PPF (shown in Figure 1) has instead been used for photocathode physics experiments.
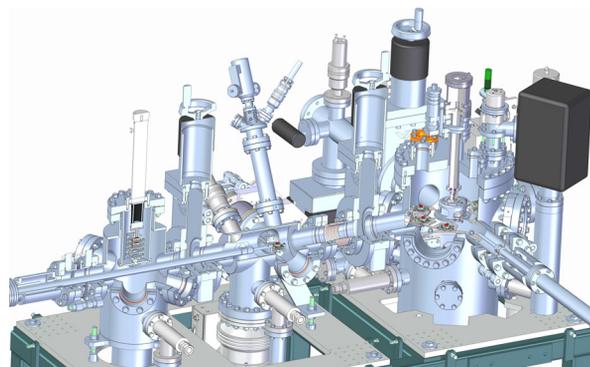

Figure 1: The ALICE PPF. This cutaway shows the loading chamber (left), the atomic hydrogen cleaning chamber (centre), and the preparation chamber (right).

Photocathodes activated in the ALICE photoinjector generally achieve a *Q.E.* between 3 and 4 % at a wavelength of 532 nm, allowing the generation of electron bunches with charge well in excess of 100 pC with the ALICE drive laser. Using custom photocathode heterostructures supplied by the ISP, the *Q.E.* routinely achieved in the PPF exceeds 15 % at 635 nm [3, 4].

PHOTOCATHODE STUDIES

Two photocathode structures were analysed, the difference being the thickness of their active layer. These will be referred to as '*thick*' and '*thin*' having active layers 2.0 μm and 0.3 μm respectively, the '*thin*' cathode delivering a fast time response. Each cathode was chemically cleaned prior to first activation by etching in HCl then rinsing in isopropyl alcohol while under a pure nitrogen atmosphere in a
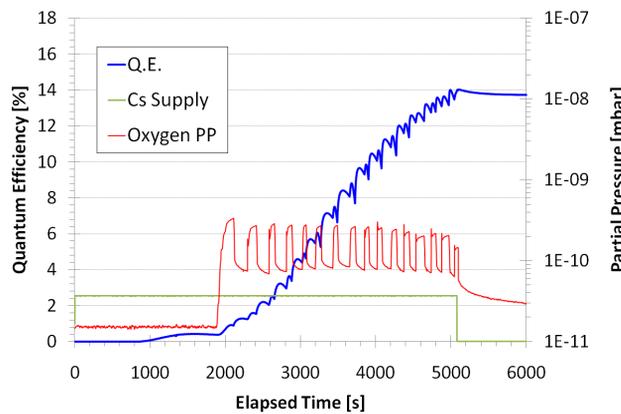
Figure 2: *Q.E.* response for a Cs-O_2:GaAs photocathode.

Figure 3: *Q.E.* response for a Cs-NF_3:GaAs photocathode.

glovebox [5, 6], then transferred to the PPF under nitrogen. They were then heat–cleaned and subsequently activated.

Choice of Oxidant, O_2 or NF_3

The PPF experimental programme has shown that there is a difference in the performance of photocathodes activated with O_2 compared to those activated with NF_3. Figure 2 shows a typical *Q.E.* response at 635 nm for a 'thick' GaAs photocathode activated to a negative electron affinity state using a Cs-O_2 co–deposition process. The green trace shows when the caesium source is operated, the red trace the partial pressure of the oxidant (plotted on the secondary axis), and the blue trace shows the evolution of the *Q.E.*

When compared to the data in Figure 3, it can be seen that the same cathode activated with NF_3 achieves a higher level of *Q.E.* These data are typical of the many activations carried out using both O_2 and NF_3 in the PPF during the course of the experimental programme [4].

It can be seen from Figure 3 that at the moment that the Cs and NF_3 supplies are cut, there is a predictable step–change in *Q.E.* which then adopts a constant level. The partial pressure needed to activate a photocathode with NF_3 is significantly higher than that for O_2, so when the gas flow is cut, the pressure drops rapidly to a level at which the *Q.E.* ceases to change further, so providing a mechanism for the operator to accurately control the final *Q.E.* of a photocathode through experience.

Long-term Reproducibility

Reproducibility in the final *Q.E.* is important to ensure that the required bunch charge can be achieved consistently over a period of time re–using the same cathode without having to remove it for chemical cleaning. It has long been known that cathodes activated using O_2 exhibit their highest *Q.E.* on their second activation, with *Q.E.* declining thereafter. This factor is particularly important for a high–current accelerator where the lifetime of a GaAs photocathode is expected to be short, thus requiring frequent photocathode re–activation.
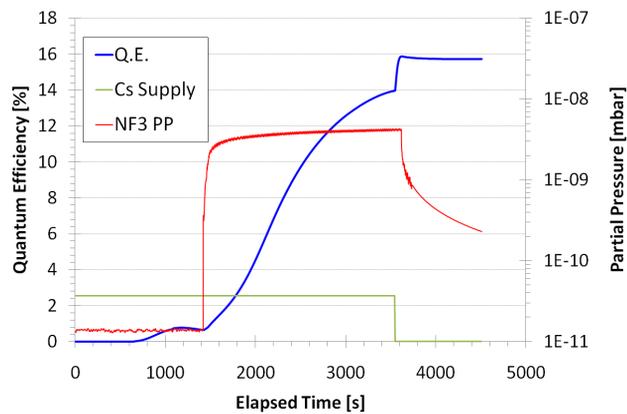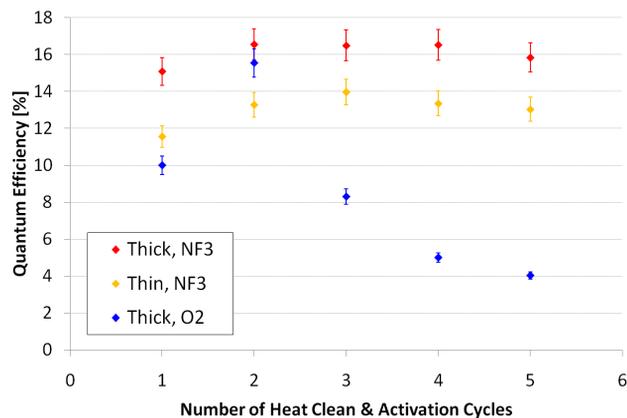

Figure 4: A comparison between the *Q.E.* achieved using both Cs-O_2 and Cs-NF_3 with 'thick' and 'thin' GaAs photocathodes.

Figure 4 shows the difference between the *Q.E.* achieved following a series of activations for both 'thick' and 'thin' photocathodes which were chemically cleaned prior to the initial activation, then simply heat–cleaned *in–situ* prior to subsequent activations.

The data shows that while *Q.E.* drops with successive activations under NF_3, the decline in performance is much less than that seen when using O_2. The reason for this behaviour when using O_2 is linked to the formation of oxides with residual gaseous species inside the vacuum system which subsequently adsorb onto the GaAs surface, and of Ga and As surface oxides. Heat–cleaning above 600 °C is then required to remove some of these oxide species. In practice, heat–cleaning is limited to 550 °C to remain below the congruent temperature for GaAs. Consequently, when re–activated, the cathode surface is not atomically–clean, so the achievable *Q.E.* is progressively reduced [7].

TRANSVERSE ENERGY SPREAD MEASUREMENTS

A key factor in photocathode performance is the transverse energy spread. This places a fundamental limit on the
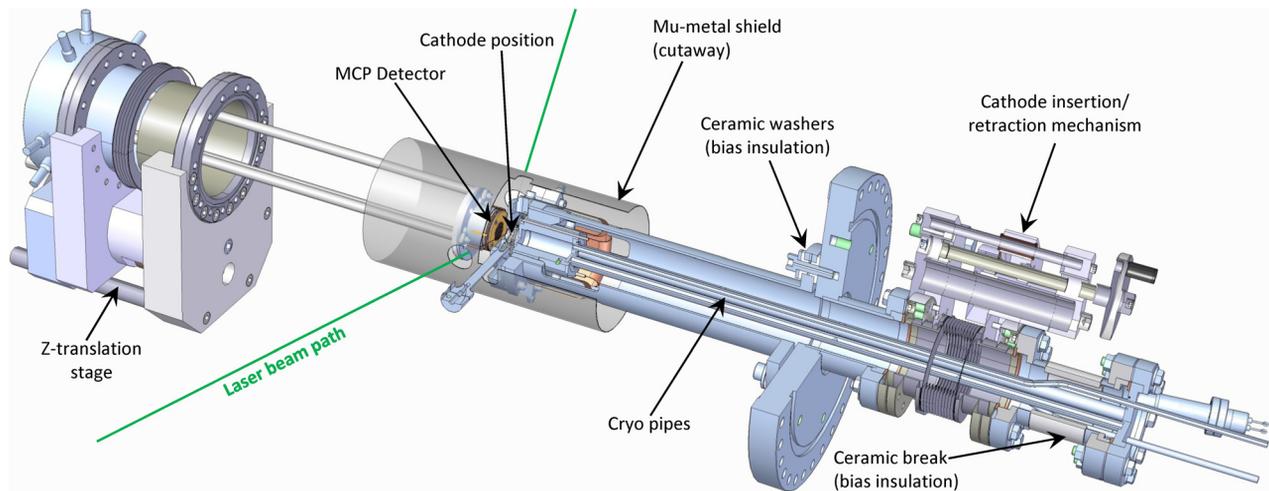
Figure 5: Schematic overview of the planned experimental system for measuring transverse energy spread. The vacuum vessel is removed for clarity, and the mu–metal shield and support stem are cut–away to show internal detail.

achievable emittance, so management and minimisation of this is essential to achieve high–brightness beams [8]. Utilising the ALICE PPF and associated assemblies, a system is being developed to permit measurement of this energy spread for GaAs photocathodes as a function of *Q.E.*

A vacuum chamber and detector system is currently being designed which will connect to the PPF, allowing photocathodes prepared under controlled conditions to be further characterised outside of the PPF. The assembly is shown in Figure 5. The cathode electrode will incorporate a side–loading slot for compatibility with the PPF cathode transportation system, with a handwheel on the back of the assembly to move the cathodes into position. The assembly will include cryogenic cooling, with copper straps to act as heat conductors, ensuring that the cathode reaches 77 K. The cathode and detector will sit on a pedestal bias around 20 V to exclude electrons generated by filaments within the vacuum system.

The detector will consist of a micro–channel plate electron multiplier (MCP), coupled to a phosphor read–out screen. A series of high–transmission grids in front of the MCP will act to retard the electrons emitted from the cathode, thereby operating as an energy filter. The assembly will be mounted on a Z–translation stage, allowing the cathode–detector gap to be varied between approximately 10 and 50 mm. The detector and cathode assemblies will be contained within a mu–metal shield to block external magnetic fields, though the shield will need holes to allow for propagation of the laser beam, and for cathode loading.

The photocathode will be illuminated at grazing incidence (approximately $10°$, as shown in Figure 5) with a CW laser whose power will be monitored continuously using a beam–splitter and photodiode combination. The voltage applied to the retarding grid will be varied, thus setting the minimum energy threshold required to reach the MCP. A camera will record images from the read–out screen as a function of retarding voltage and incident laser power.

A piezo–electric fine leak valve will allow the progressive 'poisoning' of the photocathode under test so that *Q.E.* can be controlled during measurements, thereby allowing the photoelectron energy spread to be evaluated as a function of photocathode *Q.E.*

CONCLUSIONS

The ALICE PPF has demonstrated a consistently high level of performance, particularly when using NF_3 as the oxidant. The $Cs-NF_3$ activation process produces a high level of consistency in terms of achieved *Q.E.*, though the benefits of this oxidant have to be balanced against the inherent safety issues.

The PPF will further contribute to ASTeC's GaAs research programme by its integration with an experimental system to measure the energy spread of photocathodes as a function of *Q.E.*, incident laser power, and temperature.

REFERENCES

[1] W.E. Spicer, Appl. Phys. **12**, 115 (1977).

[2] W.E. Spicer & R.L. Bell, Pub. Astron. Soc. **84** 110 (1972).

[3] 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, pages 2347-2349.

[4] N. Chanlek, University of Manchester, School of Physics and Astronomy, Ph.D. thesis, submission Sept. 2011.

[5] O.E. Tereshchenko, S.I. Chikichev & A.S. Terekhov, Appl. Surf. Sci. 142, pages 75-80 (1999).

[6] O.E. Tereshchenko, S.I. Chikichev & A.S. Terekhov, J. Vac. Sci. Tech. **A 17**, pages 2655-2662 (1999).

[7] D.A. Orlov, C. Krantz, A. Wolf, A.S. Jaroshevich, S.N. Kosolobov, H.E. Scheibler & A.S. Terekhov, J. Appl. Phys. **106**, 054907 (2009).

[8] D.A. Orlov, U. Weigel, D. Schwalm, A.S. Terekhov & A. Wolf, NIM A **532**, pages 418421 (2004).