# DESIGN OF AN UPGRADE TO THE ALICE PHOTOCATHODE ELECTRON GUN

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## Abstract

We present the design for an upgrade to the GaAs photocathode electron gun on the ALICE (formerly ERLP) accelerator at Daresbury Laboratory. This proposed upgrade includes installation of a dedicated photocathode preparation facility, with side-loading of the activated photocathodes in to the gun and a reduction of the photocathode diameter from 32 to 10 mm. The preparation facility forms a common vacuum system with the gun, isolated by a gate valve, permitting significant improvement in the gun vacuum and a reduction of caesium vapour contamination improving gun stability at high voltage. This preparation facility will reduce the time required for a photocathode change from weeks to hours. The facility should also provide photocathodes with improved quantum efficiency due to a more controllable preparation procedure, and allows performance of experiments using photocathodes activated to different levels of electron affinity.

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## INTRODUCTION

The electron gun currently under commissioning at Daresbury Laboratory for the ALICE Energy Recovery Linac [1] is a modified version of the gun developed for the Jefferson Laboratory Infrared FEL [2]. This is a 350 kV DC gun, using GaAs photocathodes illuminated by laser pulses at a wavelength of 532 nm. The pulses have a FWHM length of 7 ps and a repetition rate of 81.25 MHz. A pulse stacker is used to generate 13 or 28 ps FWHM pulses, as required. A modulation system comprised of a mechanical chopper, shutter and Pockels cell define the laser pulse train, whose lengths can vary from just a single pulse to 100 μs macropulse. Activated *in situ* by means of a $(Cs, NF_3)$ "yo-yo" procedure, the photocathodes are able to deliver electron bunches of 80 pC (from a maximum of 140 pC immediately after activation), corresponding to an average macropulse current of 6.5 mA.

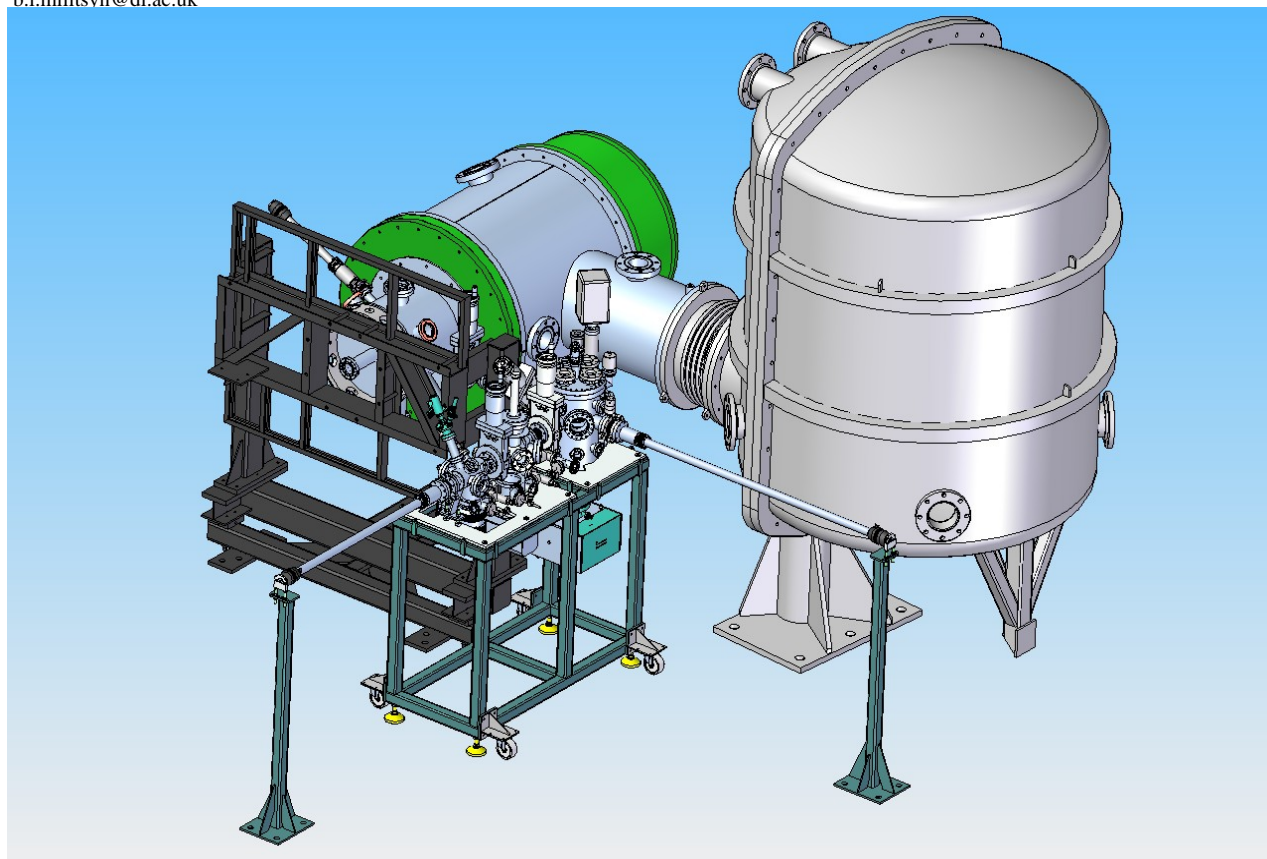Currently, replacing a photocathode takes weeks due to



Figure 1: General view of the ALICE photocathode gun equipped with a photocathode preparation facility.

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the requirement to break the vacuum, replace the photocathode, then restore gun vacuum to its operation level of $10^{-11}$ mbar. The focus of the upgrade is the introduction of an external photocathode preparation facility which permits photocathode replacement without a need to break the vacuum. This will reduce the downtime taken for changeover to a matter of hours, a fact which is especially important for guns delivering average currents of 10 mA or more at user facilities when the operation lifetime of a photocathode does not exceed a few days. Photocathode preparation facilities for GaAs-based electron injectors have been widely used by the nuclear physics community in the production of polarized or ultracold electrons. Recently, this type of facility has also been adopted by the FEL community, and an extensive reference list is available on this subject.

## OVERVIEW

The preparation facility consists of three vacuum chambers, and is conceptually similar to that used at [3]. It comprises a photocathode loading chamber, a hydrogen cleaning chamber, and an activation chamber. These chambers are isolated by gate valves, and photocathodes are transferred between them using a magnetic manipulator. A second magnetic manipulator is used to transfer photocathodes between the activation chamber and the electron gun. This design is itself a prototype for a preparation system which will permit the operation of high average current photocathode guns. Fig. 1 shows how the preparation facility integrates with the existing ALICE photoinjector gun.

Photocathodes will first be chemically cleaned in a nitrogen-filled glove box. They will then be transferred into the loading chamber in a hermetically-sealed transport vessel which can hold up to four photocathodes. The
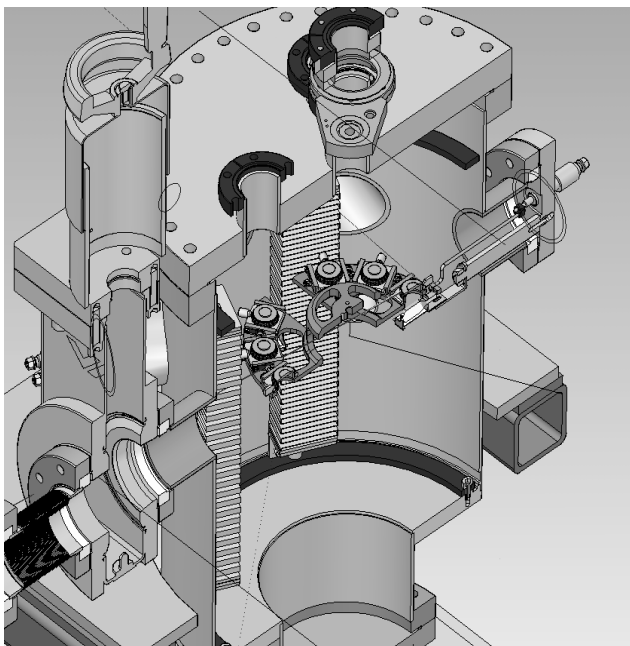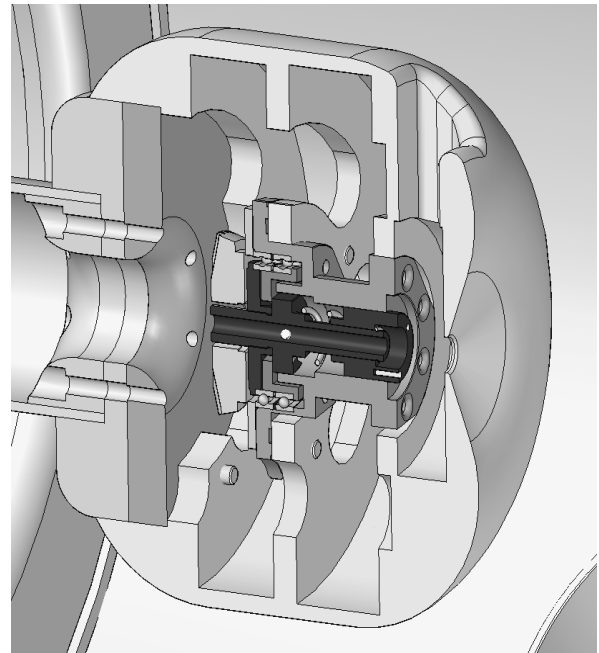
Figure 3: Preliminary design for the cathode ball.

photocathode surface can then be treated in the hydrogen cleaning chamber with atomic hydrogen provided by an ion-free thermal cracker. Clean photocathodes are then transferred to the adjoining activation chamber where they are thermally cleaned and activated with (Cs,O) or (Cs,NF$_3$). The quantum efficiency (*Q.E.*) during photocathode activation is monitored at the operation wavelength of 532 nm. Up to ten photocathodes can be stored on a carousel in the activation chamber, as shown in Fig. 2.

## CATHODE BALL

Photocathodes are loaded into the ball through a side-slit using a magnetic manipulator. In order to minimise field distortion, the slit has been positioned on the flat part of the ball surface. A mechanism driven by a "magnetic screwdriver" engaged in a hole with radiussed edges moves the photocathode forward and locates it firmly on the back side of the cathode electrode, providing efficient thermal contact of the photocathode substrate with the heat sink. The cathode ball is equipped with a focussing electrode in order to provide optimised transportation and local emittance compensation of the electron beam [4].

## FAST SEMICONDUCTOR PHOTOCATHODES

When using semiconductor GaAs photocathodes in an electron injector to drive an FEL, several parameters have to be 'tuned'. These parameters are as follows:

(i) the photocathode response time should be $\leq 10$ ps;

(ii) the photocathode should provide electron bunches at a high repetition rate, which might exceed 1 GHz;
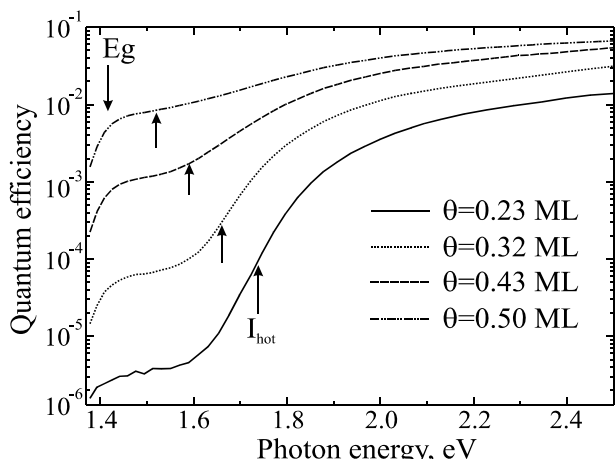
(iii) the bunch charge should be in the range 10-1000 pC;

Figure 2: Cross-section of the activation chamber.

Figure 4: Quantum efficiency spectra of p-GaAs(Cs) – photocathode for different Cs coverage θ.

(iv) the average current should be high enough, not less than 10 mA;

(v) typical transverse emittance of the emitted electrons should be less than 1 $\pi$·mm·mrad.

The physical phenomena within GaAs photocathodes which control these parameters are well known, and it has been demonstrated experimentally that control of each parameter is feasible with different photocathode materials. A number of questions remain to be answered before all parameters can be addressed within a single photocathode. Perhaps the most significant question is:– "*does one really need to bring photocathodes to the Negative Electron Affinity (NEA) state to generate FEL-compatible electron beams, or can GaAs photocathodes with low Positive Electron Affinity (PEA) be used for this purpose instead?*"

PEA photocathodes can easily achieve a time response of 1 ps because non-thermalised photoelectrons with thermalisation times on the picosecond-scale dominate photoemission from heavily p-doped PEA GaAs photocathodes [5]. The maximum achievable repetition rate for electron bunches generated by PEA photocathodes should exceed that of NEA photocathodes made of a similar GaAs layer. This is because the escape probability of 'hot' (non-thermalised) photoelectrons is less sensitive to the position of the vacuum level compared to the escape probability for thermalised electrons [6]. Considering that photoemission of 'hot' electrons is also less sensitive to the surface photovoltage effect [6], one may conclude that both electron charge per bunch and the average current of PEA photocathodes are mainly defined by the intrinsic Q.E. of the photocathodes.

In order to investigate the dependence of Q.E. on photon energy for PEA photocathodes, we have activated an epitaxial layer of p-GaAs ($p = 8 \times 10^{18}$ cm$^{-3}$) with Cs only and have measured Q.E. spectra for different Cs coverage, as shown in Fig. 4. One can see that there are two thresholds in the Q.E. spectra, marked with arrows. The position of low energy threshold corresponds to the energy gap $E_g$ for GaAs, and the position of $I_{hot}$ corresponds to the vacuum level. The energy difference between these two thresholds is equal to the effective electron affinity $\chi^*$, which decreases from 0.31 eV for a Cs exposition of 0.23 ML to 0.09 eV at 0.5 ML. Photoemission of thermalised photoelectrons dominates at $E_g < \hbar\omega < I_{hot}$. At $\hbar\omega > I_{hot}$, non-thermalised photoelectrons begin to contribute to photoemission and Q.E. increases rapidly. One can see from this that photoemission of thermalised photoelectrons from PEA photocathode is low, less than 0.1%. It is also clear that Q.E. at $\hbar\omega = 2.5$ eV exceeds 6%, though this is much less than the Q.E. = 40% obtained at $\hbar\omega = 2.5$ eV for a fully activated p-GaAs (Cs,O) photocathode in the NEA state [7]. Nevertheless, it is sufficient for the generation of high photocurrents [8]. The only parameter of a PEA photocathode which should be worse than that of a NEA photocathode is the transverse energy spread of the emitted non-thermalised electrons.

It must be emphasized that the thickness of the active layer in an NEA photocathode optimised for 10 ps time response should be of the order of 200 nm [9]. This is not sufficient for the complete absorption of the incident light with $\hbar\omega \approx E_g$. Therefore, the Q.E. of 'fast' NEA photocathodes will be significantly less than that of bulk material, so the generation of high average photocurrent will require significant laser power.

## SUMMARY

In this paper, we described an upgrade to the ALICE ERL photocathode electron gun concerning the installation of an external photocathode preparation facility and replacement of the stem-mounted back-loading photocathode with a side-loading 'puck'. The possibility has been discussed of obtaining short response time and high repetition rate in GaAs photocathodes. It has been shown experimentally that bulk GaAs photocathodes activated to low Positive Electron Affinity state which potentially have a response time of several picoseconds are able to emit electrons with a Q.E. of few per cent at a wavelength which is comparable to that used to drive a thin layer NEA GaAs photocathodes having similar response time.

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