3.18 High Voltage DC Photoinjector Development at Daresbury Laboratory

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Abstract:
STFC Daresbury Laboratory currently operates a 350 kV DC electron gun using caesiated GaAs photocathodes to provide bunches up to a nominal 80 pC up to an average current of 6.5 mA. This serves as the injector for ALICE (Accelerators and Lasers In Combined Experiments) - a 35 MeV energy recovery linac based on 1.3 GHz superconducting RF technology. An upgrade to the electron gun is under way to incorporate a three-chamber photocathode preparation facility forming a load-lock with the gun chamber. This will allow rapid changeover of photocathodes without breaking the gun vacuum and improve photocathode activation procedure. Initial results of the activation in the commissioned preparation facility have produced quantum efficiencies of up to 15 % at 635 nm. The status of the project and ongoing research and development is presented here.

3.18.1 **Introduction**

GaAs photocathode based high voltage DC electron guns are operational at a number of different laboratories worldwide as injectors for energy recovery linacs and free electron lasers due to their potential to deliver beams of high average current (up to 100 mA in CW mode) with a relatively low normalized emittance of a few mm·mrads. DC guns with GaAs and other III-V family semiconductor photocathodes have typically being used as a source of polarized electrons at energies around 100 keV. Since the minimum emittance, $\varepsilon_{\min}$, of the produced electron beam is related to the electric field strength on the cathode surface, E_c, as [1]

$$\varepsilon_{\min} = \sqrt{\frac{q}{4\pi\varepsilon_0 E_c}\frac{k_B T_\perp}{m_e c^2}} \quad (1)$$

there is a drive towards higher voltage. GaAs based DC guns have been employed at TJNAF [2], Daresbury Laboratory [3] and JAEA/KEK [4] with power supplies rated to 500 kV and at Cornell University [5] with a 750 kV power supply.

3.18.2 **ALICE Gun**

The electron gun, shown in Figure 1, at Daresbury Laboratory is a modified version of the gun developed for the TJNAF Infra-Red FEL [2]. This operates at a nominal 350 kV with the standard ceramic insulator. The GaAs photocathodes are currently activated in-situ in the gun chamber with Cs and O_2 or NF_3 in a “yo-yo” procedure. The photocathodes are illuminated by a mode-locked Nd:YVO_4 laser, frequency doubled to 532 nm [6]. This provides 7 ps FWHM pulses at a repetition rate of 81.25 MHz. A pulse stacker is used to generate either 14 or 28 ps pulses. The pulse train length can be varied from a single bunch up to 100 µs with a train repetition rate of up to 20 Hz. The nominal bunch charge is 80 pC with a corresponding average train current of 6.5 mA. The maximum achieved quantum efficiency (QE) of the photocathodes has been 3.7 % and a maximum bunch charge of ~ 150 pC has been measured from the cathode. Typical operational photocathode 1/e lifetime is 100-250 hours with a dark lifetime measured at over 900 hours. A typical lifetime plot is shown in Figure 2.

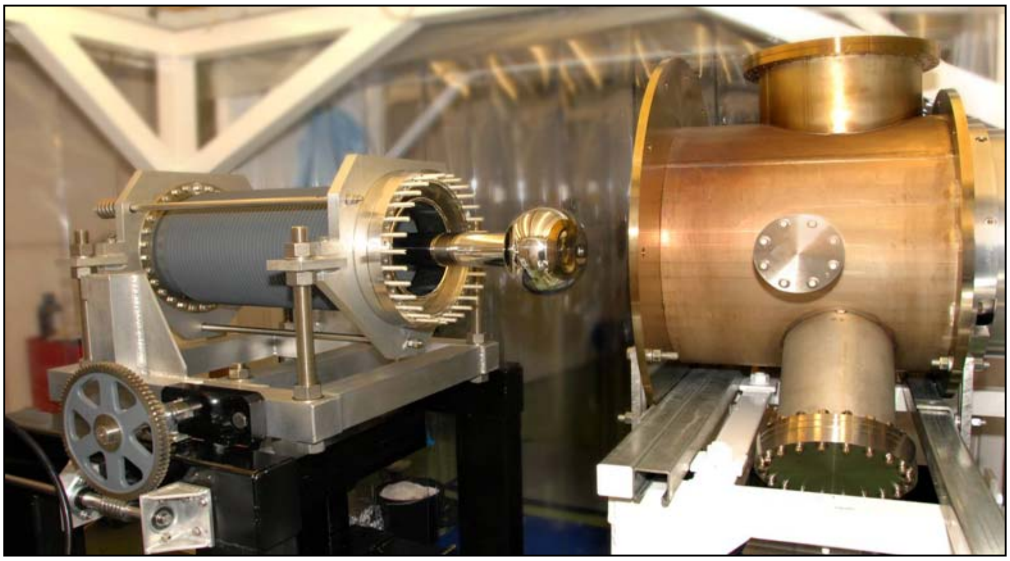

Figure 1: The ALICE electron gun before final assembly, showing ceramic and cathode ball.

The main modification to the TJNAF gun design is the use of a single large ceramic with bulk-doped controlled resistivity as the high voltage insulator. Whilst initially successful, with routine conditioning to 450 kV (up to a maximum of 485 kV), the long-term reliability of the brazing joints under load due to thermal cycling during baking has been poor. A collaboration between Daresbury Laboratory, TJNAF and Cornell University has resulted in design and delivery of an insulator with a modified taper near the brazing. In the interim period, ALICE has been operating with a smaller, two-piece insulator, limiting the operating voltage to ~250 kV. Field emitters on the current photocathode have further reduced operational voltage to 230 kV. A reduced bunch charge between 20 and 60 pC has been using whilst commissioning ALICE to minimize downtime due to photocathode re-activation and to minimize beam loading effects in the superconducting RF booster.

Figure 3 shows QE maps of the current ALICE photocathode at the end of an operational cycle, and just after heat cleaning and re-activation. At the end of operations, the whole photocathode surface is reduced in QE. The large hole in the centre of the QE map is due to ion back-bombardment but is fully recovered after the heat cleaning and re-activation procedure. The smaller hole in the QE maps is a likely field emission point.

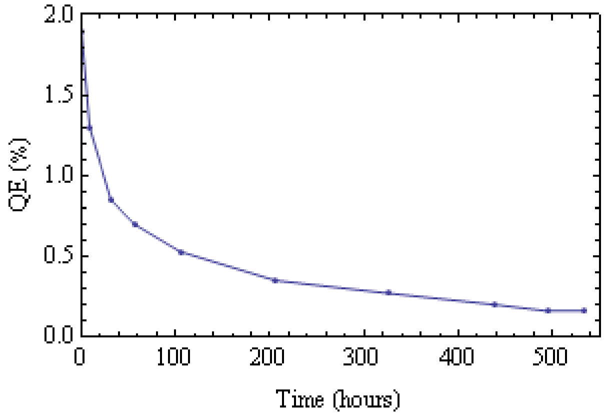

Figure 2: Example QE lifetime plot for photocathode during ALICE commissioning showing 1/e lifetime ~ 250 hours.

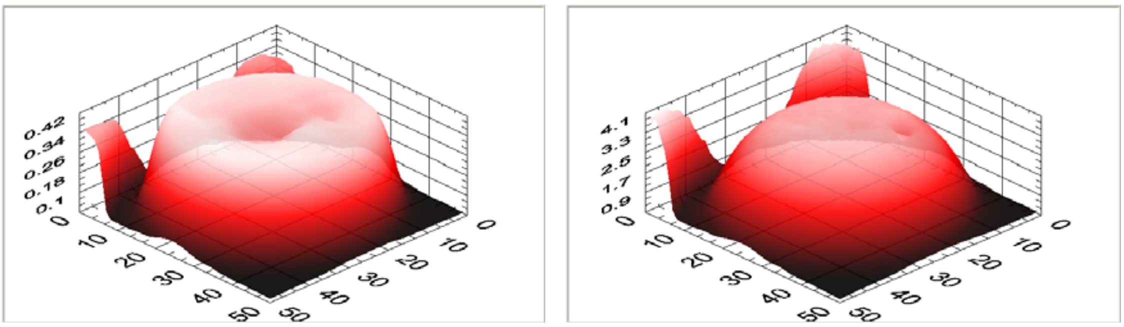

Figure 3: Typical QE maps at the end of the operational cycle (left) and after a full cathode re-activation including heat cleaning (right).

3.18.3 **ALICE Gun Upgrade**

An upgrade to the ALICE gun is currently underway, for installation in 2011, involving development of new photocathodes, a “load-lock” photocathode preparation facility (shown in Figure 4), and a side loading transport mechanism of the photocathode into the gun. These elements are described below. An extended gun beamline incorporating a suite of diagnostics useful for ALICE operations as well as testing different photocathodes is also being considered and is described in [7].

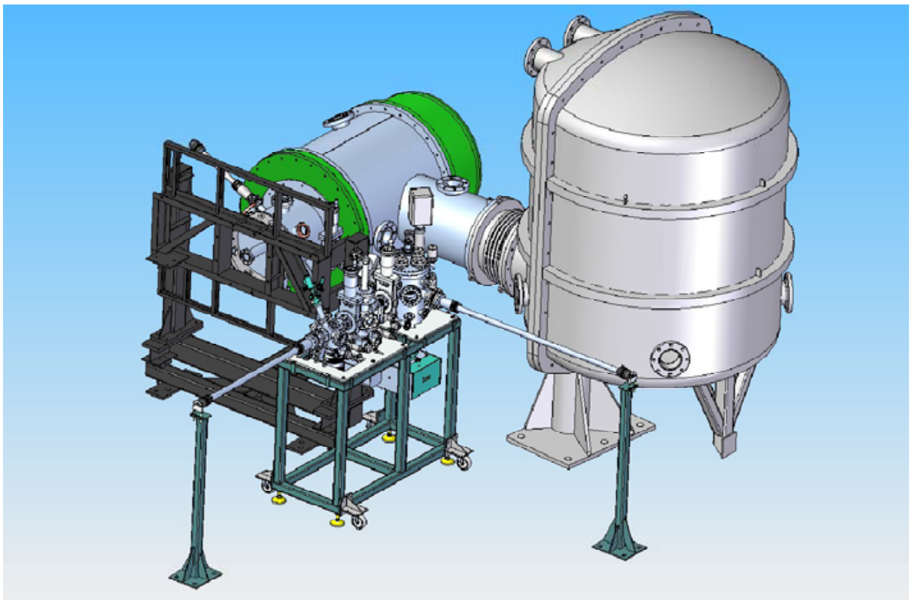

Figure 4: General view of the ALICE gun equipped with the photocathode preparation facility.

3.18.3.1 *Photocathode Development*

Originally III-V family photocathodes such as GaAs, GaAsP, InGaAsP were mainly used in DC guns for production of polarised electrons. As grown, these materials have a positive electron affinity (PEA), which for GaAs is 4 eV. In order to make GaAs photocathodes able to emit electrons when illuminated by 532 nm light, the electron affinity should be reduced to less than 1 eV - or even brought to a negative value. This activation process basically comprises deposition on the atomically-clean photocathode surface of a thin layer of Cs and an oxidant, typically O_2 or NF_3. Before the activation, the surface of the photocathode is chemically etched and heat cleaned in order to remove As and Ga oxides.

GaAs photocathodes place extremely high demands to operational vacuum conditions as they are very sensitive to the presence of oxidants in the residual atmosphere. For example the 1/e lifetime of GaAs does not exceed $2{\cdot}10^{-8}$ mbar·s of oxygen exposition [8]. The pressure in typical GaAs guns is of the level of 10^{-11} mbar. Low operational life time is also an issue. The dominant mode of GaAs degradation is bombardment of its surface by back streaming ions.

ALICE currently uses GaAs photocathodes with a diameter of 25 mm. The new cathode assembly of the gun, however, has been designed to accommodate photocathodes with an emission surface diameter of 10 mm, as shown in Figure 5. This is because the laser only illuminates an area ~ 4 mm in diameter and a smaller active area could help reduce the beam halo. The preparation facility allows a variety of III-V photocathodes to be tested in the ALICE photoinjector, with varying active layer composition, thickness, and electron affinity.

Figure 5: GaAs photocathodes on molybdenum substrate

Recent measurements of the QE spectra indicate that GaAs activated to PEA, where it is capable of picosecond level response times, has a QE of a few per cent [9]. This is enough to deliver bunches with a charge of several dozen pC. Figure 6 shows QE spectra for PEA GaAs photocathodes activated with Cs only to different levels of Cs coverage. The position of low energy threshold corresponds to the energy gap Eg 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. Figure 6 also shows measured longitudinal energy distribution of electrons emitted from a PEA GaAs photocathode, indicating that the trade-off for a fast response time is that the energy spread is relatively large.

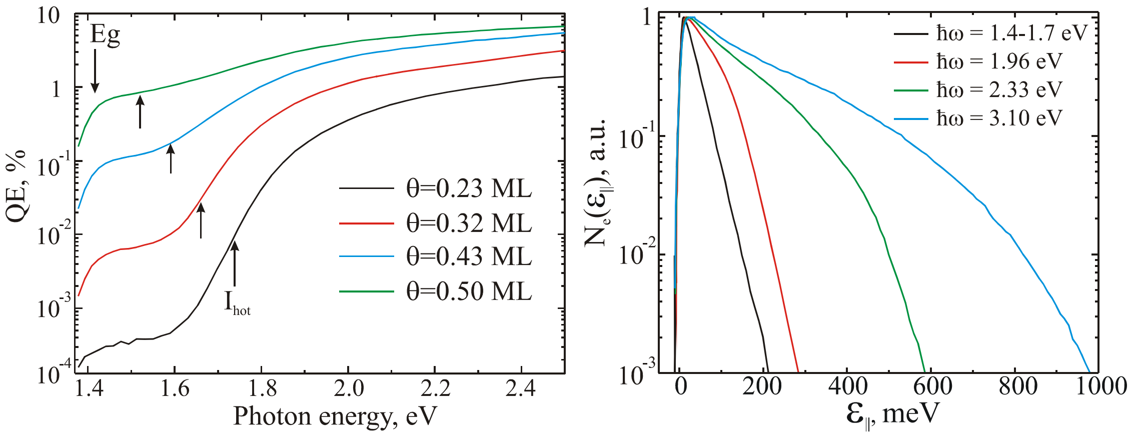

Figure 6: QE spectra of p-GaAs(Cs) –photocathode for different Cs coverage θ (left),and longitudinal energy distribution curves at different photon wavelengths for a PEA GaAs photocathode (right).

3.18.3.2 ***Photocathode Preparation Facility***

As the photocathodes are currently activated in situ in the ALICE gun chamber, the process of photocathode changeover takes weeks due to the need to break and restore the vacuum to 10^{-11} mbar whilst replacing the photocathode, including an extensive bakeout at 250°C. A load-lock system will allow photocathode replacement to be made without breaking the vacuum thus reducing the time taken to a matter of hours. A separate preparation facility also removes the activation process of the GaAs photocathodes outside of the gun, thus reducing the introduction of contaminants into the gun vacuum system and eliminating the risk of spreading Cs onto other parts of the cathode ball - which causes undesired field emission, and on the high voltage insulator - which reduces maximum achievable voltage. Such a facility has currently been built and commissioned at Daresbury Laboratory with plans for later installation onto the ALICE electron gun.

Figure 7: The assembled photocathode preparation facility.

The preparation facility, shown in Figure 7, consists of three chambers: a loading chamber where photocathodes are introduced to the system, a hydrogen-cleaning chamber to remove contaminants from the photocathode surface and a preparation chamber where photocathodes are activated. A magnetic manipulator is used to transport the photocathode between the three chambers. Before assembly, the components of facility were vacuum fired at a temperature of 950ºC for five hours to deplete the 316LN stainless steel of hydrogen.

Photocathodes are introduced into the loading chamber, as shown in Figure 8, by a z-translation stage containing a magazine holder capable of accommodating four photocathodes. To load new photocathodes, the magazine holder is removed from the loading chamber and transported under dry nitrogen to a nitrogen-purged glove box where new photocathodes are chemically etched. The etched photocathodes are inserted into the magazine holder, and the z-stage is closed such that the ‘O’ ring seals. The photocathodes are thus stored in a leak tight nitrogen environment. The z-stage is then re-inserted in to the loading chamber, the ‘O’ ring seal opened and the chamber evacuated to ensure the photocathodes are not exposed to any contaminants from the atmosphere. The pumping system of the loading chamber includes an ion pump and an oil-free preliminary pumping station. After the photocathode is placed into the loading chamber, it is pumped down to a pressure of 10^{-9} mbar.

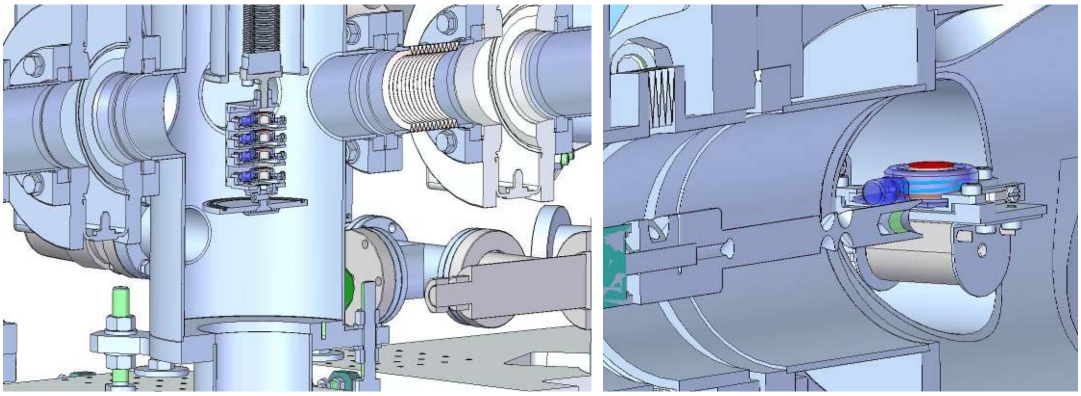

Figure 8: Section views of (left) the loading chamber, and (right) the hydrogen cleaning chamber.

The hydrogen cleaning chamber, shown in Figure 8, is used to initially process photocathodes before activation, and to process used photocathodes before re-activation. The photocathode is heated to ~300 ºC via the use of a halogen bulb. The bulb is shielded by tantalum screen to avoid any radiative heating of other components whilst focusing the heat onto the photocathode, thus minimising the power requirements. The hydrogen cleaning process makes use of a thermal gas cracker that uses electron bombardment of a tungsten capillary to thermally dissociate the gas passing through it. Given the right conditions the thermal cracking efficiency of hydrogen is very high and this is important in order to minimise the number of H^+/H^- ions in the cleaning process.

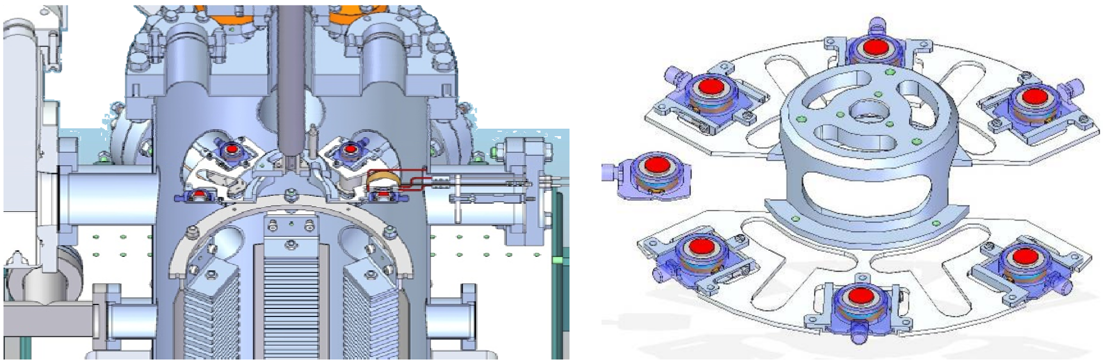

Figure 9: Section view of the activation chamber (left), the photocathode carousel (right).

Figure 9 shows the activation chamber - which contains a carousel capable of holding six photocathodes. A photocathode, transferred from the hydrogen cleaning chamber, is first heat cleaned. There are two heating positions in the chamber, each using the same halogen bulbs as in the hydrogen cleaning chamber. Finite element analysis shows that the temperature of the neighbouring photocathodes should remain less than 100°C during the heat cleaning process. Once cooled, the heat cleaned photocathode is rotated into the single activation position. Cs dispensers are positioned within 10 mm of the photocathode surface, as is the charge collector used to measure the photocurrent. The O_2/NF_3 is injected into the system via a piezo-electric fine leak valve which is positioned on the conflat flange that sits directly above the photocathode. XHV conditions are maintained in the activation chamber by means of ion pumps and six non-evaporable getter strips. The typical pressure is less than 10^{-11} mbar, with partial pressures of oxygen, water vapour and CO_2 less than 10^{-14} mbar.

The photocathode preparation facility was successfully commissioned in spring 2009, with a maximum achieved quantum efficiency of 15% at a wavelength of 635 nm. Figure 10 shows the “yo-yo” procedure used.

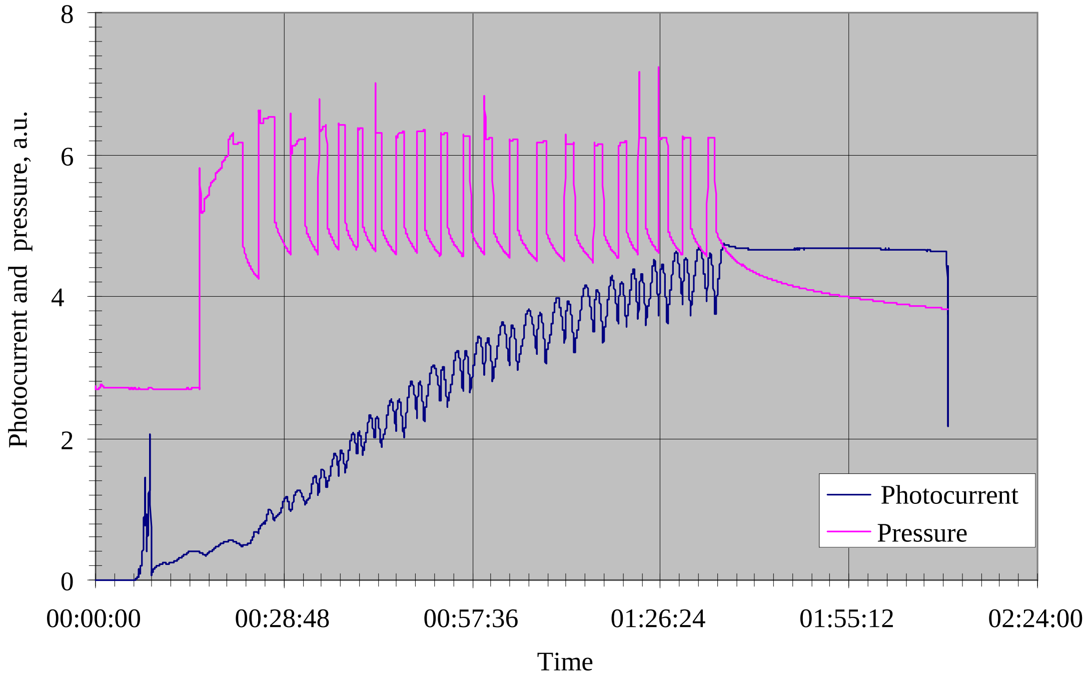

Figure 10: Cs-O activation of a GaAs photocathode using the “yo-yo” procedure.

3.18.3.3 *Cathode Ball Design*

It is proposed that the photocathodes are loaded from the preparation chamber into the side of the gun, in order to avoid disruption to the existing ALICE infrastructure. This involves a re-design of the cathode ball from the present rear-loading mechanism. The ball requires a slot in the side for loading of the photocathode. This has been positioned on the cylindrical part of the ball surface to keep the field distortion low. The photocathode then has to be moved forward into position, requiring a second slot further back in the cathode ball for insertion of a magnetic screwdriver to drive the winding mechanism. A third slot, perpendicular to the loading slot, is required as a viewport to ensure the photocathode is loaded properly. Figure 11 shows the electric fields at 350 kV on the cathode ball surface, as modelled in CST Studio [10]. The electric field has been kept lower than 10 MV/m on the curved surface of the ball and also around the edges of the slots. A focussing electrode has been added and optimised by performing beam dynamic simulations in ASTRA [11]. Figure 12 shows that the transverse beam properties for the new gun design compared to the existing gun which lacks the focussing electrode.

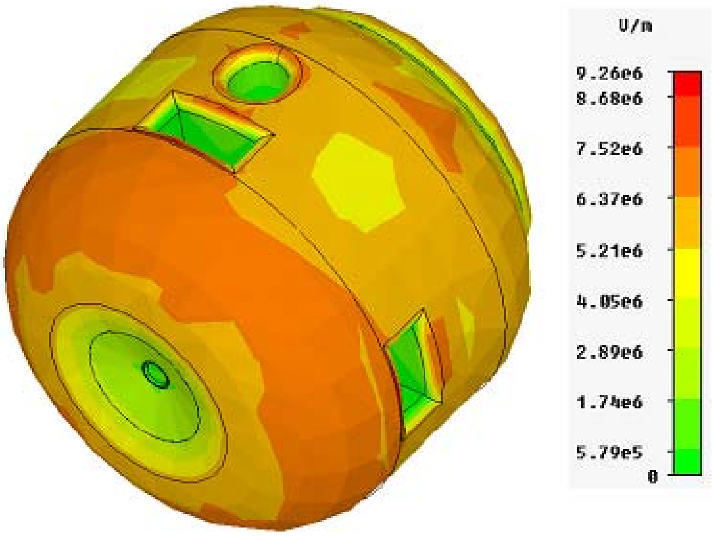

Figure 11: The cathode ball with slots and focusing electrode showing electric fields.

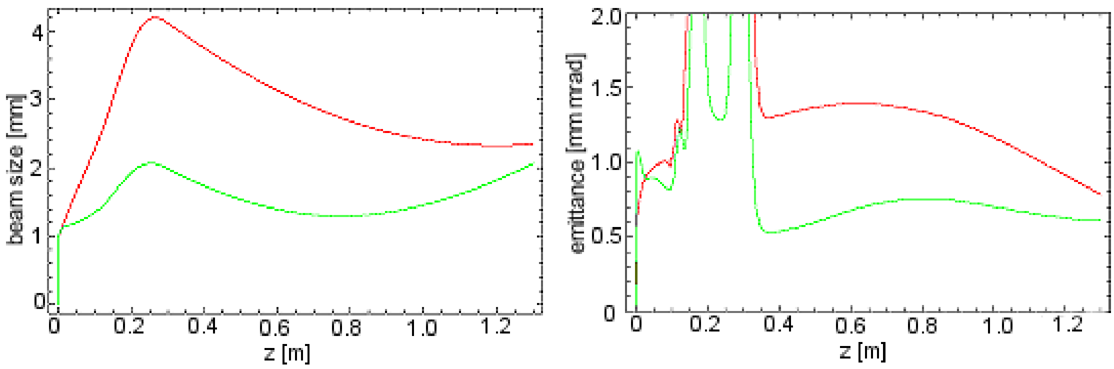

Figure 12: RMS beam size (left) and transverse emittance (right) for the new gun design (green) compared to the current gun (red) including a 330 G solenoid at 0.25 m.

3.18.4 **Summary**

The GaAs based 350 kV DC gun for ALICE has been operational since August 2006 – with a maximum QE of 3.7 % achieved and dark lifetime in excess of 900 hours. Following development of III-V photocathodes on different substrates and activated to differing levels of electron affinity, a three-chamber photocathode preparation facility has been constructed at Daresbury Laboratory. This has successfully been commissioned and GaAs photocathodes have been activated with a maximum QE of 15% measured at 635 nm. This facility will be installed on the ALICE gun in 2011, enabling faster photocathode changeover and better vacuum conditions in the gun. The design of the photocathode preparation facility means that in future additional chambers can be added, allowing testing of multi-alkali photocathode materials, such as K2CsSb, in the ALICE electron gun. These should offer high QE (up to 20 %) at the 532 nm wavelength of the current ALICE photoinjector laser and have a fast response time. They could also offer a longer lifetime than GaAs photocathodes since they have shown a much higher robustness under exposition to oxygen [12]. However, their stability to ion back-bombardment is unknown and has to be investigated.

3.18.5 References

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