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## *EUROPEAN FEL Design Study*

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                          Current DC Photo-injector Development

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# High Average Current DC Photoinjector Development

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A GaAs photocathode based DC electron gun has been designed to provide an average current of 100 mA by delivering bunches of charge 77 pC at 1.3 GHz. To operate at high current, the gun contains a multi-chamber photocathode preparation facility, and new photocathode structures are under development. Electrostatic calculations have been carried out to optimise the electrode design at 500 keV. Beam dynamic simulations have been carried out for transport of the beam through a 10 MeV injector line which show a final electron beam with normalised transverse emittance of less than 2.5 $\pi$·mm·mrad, longitudinal emittance of less than 10 $\pi$·keV·mm and a bunch length less than 2.5 ps. Further simulations show that this beam quality is achievable with a photoinjector drive laser stability of up to 1 ps.

## 1. Introduction

   Design work is presented for the development of an injector capable of delivering a high quality 100 mA electron beam of bunch charge 77 pC at 10 MeV. This injector was designed for the energy recovery loop of the 4GLS project at Daresbury Laboratory [1]. The injector would feed a superconducting linac accelerating the beam to 550 MeV before passing through an arc and a succession of spontaneous undulator light sources followed by a vacuum ultra-violet free electron laser (VUV-FEL). The injector is based on a DC GaAs photocathode electron gun. This paper discusses the photocathodes and preparation facilities required for operating such a gun at high average current, and presents electrostatic simulations of the electron gun at 500 keV and beam dynamic simulations of the electron beam from the photocathode through a 10 MeV injector line, including studies of the jitter of the photoinjector drive laser.

## 2. Injector Design

### 2.1    Injector Requirements

   For the 4GLS High Average Current Loop the injector needed to provide a beam of 10 MeV with good beam quality for the insertion devices. These require a normalised emittance of 2 $\pi$·mm·mrad and an uncorrelated energy spread of less than 0.1 %. The injector also needed to provide a bunch length of less than 3 ps in order for the compression system to achieve the required 100 fs at the entrance of VUV-FEL when using sextupoles for linearization [2]. The average current of 100 mA can be reached by filling every 1.3 GHz RF bucket with a bunch of charge 77 pC.
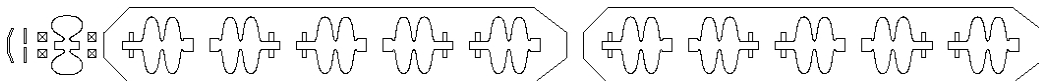
### 2.2    Injector Overview



Figure 1: Schematic layout of the injector.

The DC electron gun running at 500 kV is followed by a solenoid and a single-cell buncher cavity based on the Cornell design [3]. The buncher cavity is followed by a second solenoid and two 5 MeV superconducting Cornell booster modules [4]. Fig. 1 shows a schematic layout of the injector. The accelerating modules each contain five two-cell cavities which have independently-adjustable phase and gradients. The 2-cell cavities have been designed to propagate out higher order modes through an enlarged beam pipe on one side where they are damped by ferrite absorbers. Each cavity has two coaxial couplers to deliver a total of 100 kW of RF power and to minimise the transverse kick.

## 3. GaAs Photocathode Development

Work is being carried out in collaboration with the Institute of Semiconductor Physics in Novosibirsk to develop a photocathode to meet the requirements of delivering 100 mA with a goof beam quality. The photocathode should provide a short time response approaching 20 ps. However, the longitudinal beam profile from a bulk GaAs photocathode possesses an undesirable long tail due to the long absorption and diffusion lengths in the semiconductor [6]. A profile approaching a Gaussian can be achieved by limiting the active layer thickness to as low as 200 nm [7]. Assuming the photon energy is equal to the semiconductor band gap, an active layer this thin does not allow complete absorption of incident light. This reduces the $Q_e$ to only a few percent compared to the 40% that can be achieved with a bulk material. Therefore to reach the desired 100 mA the photocathode will have to be illuminated with laser power approaching 50 W. This level of power heats the GaAs to a temperature at which the active layer begins to decay. Very efficient photocathode cooling is required and this has led to the development of new structures on durable substrates, since conventional photocathodes are too fragile to be pressed on to the mounting position with sufficient pressure to provide low thermal resistance. Both reflection-mode photocathodes bonded to molybdenum, and silicon and transmission-mode (for back-illumination) on sapphire, are currently under development.

## 4. Photocathode Preparation Facilities

The main limiting factor in the gun performance is the operational lifetime of the photocathode which is restricted by the back ion stream. Residual gas becomes ionized by the primary electron beam and then accelerated towards the photocathode surface, degrading it, resulting in a decrease in the quantum efficiency ($Q_e$) over time; an extremely high level of vacuum is required to limit this damage. The photocathode lifetime is expected to be around 24 hours and so to minimise downtime between cathode changes, the gun will be equipped with a multiple-chamber cathode preparation facility as shown in Figs. 2 and 3.

The photocathode will be installed in the gun using a load-lock system from a preparation chamber. This chamber may hold up to 10 photocathodes and includes facilities for heat treatment and activation of the photocathodes with Cs and $O_2$ or $NF_3$. In addition it is proposed to have a dedicated hydrogen cleaning chamber to repair degraded photocathodes. Before loading into the gun system, new photocathodes will be chemically cleaned in a nitrogen-filled glove box.
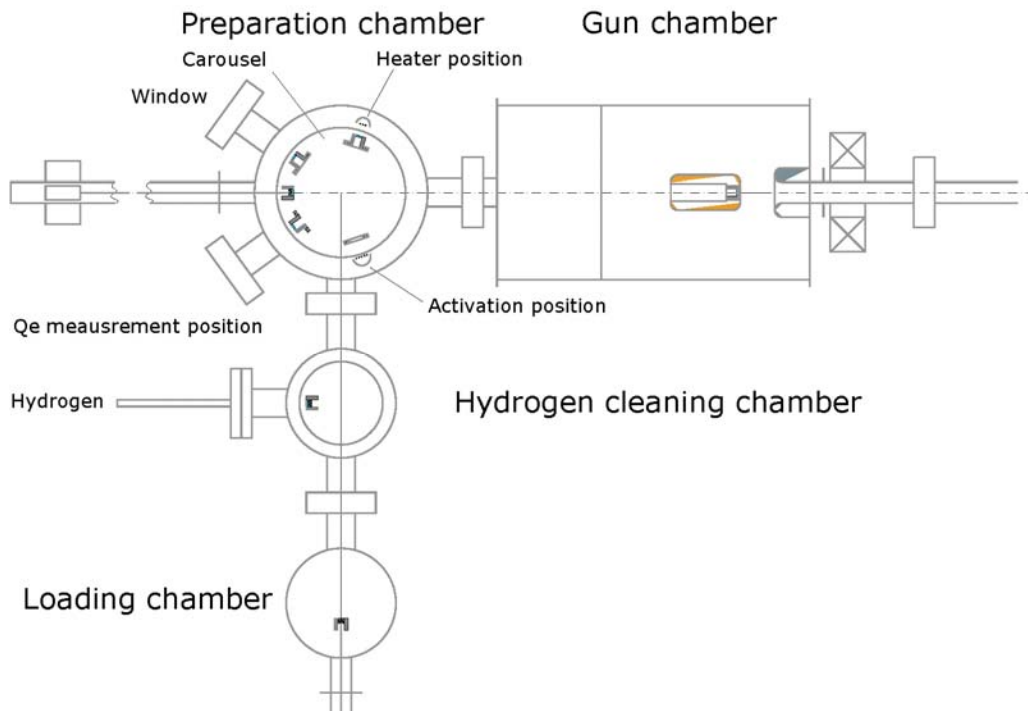
Figure 2: Overview of the chambers and facilities of the photocathode electron gun.
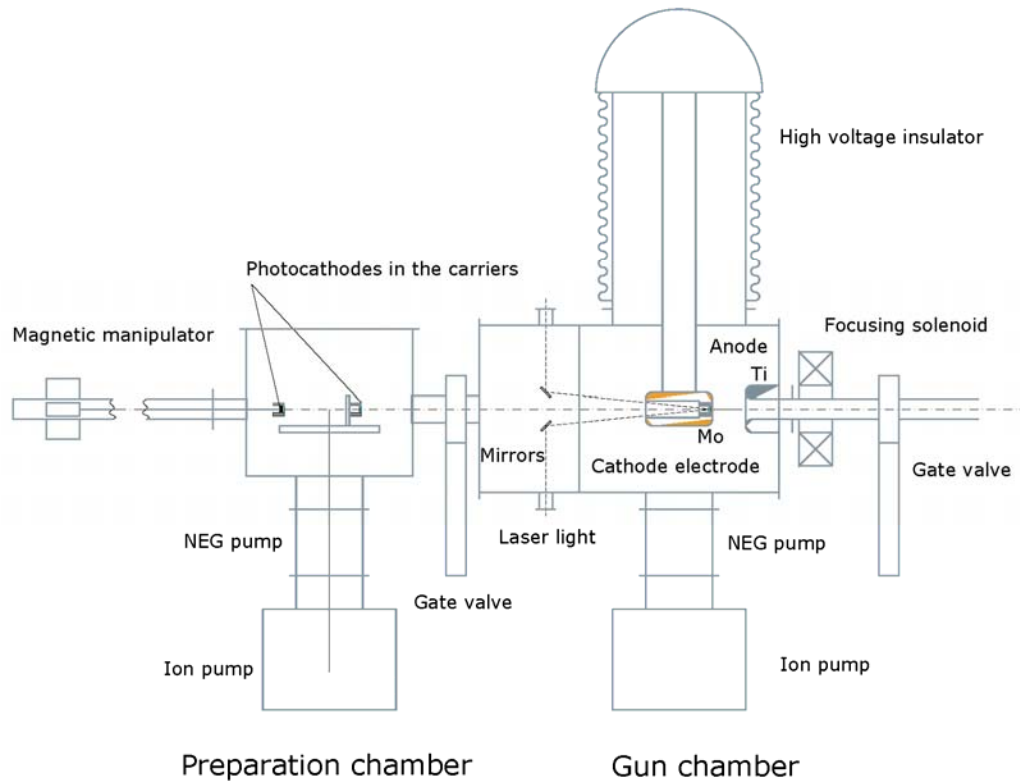


Figure 3: Schematic of the electron gun.
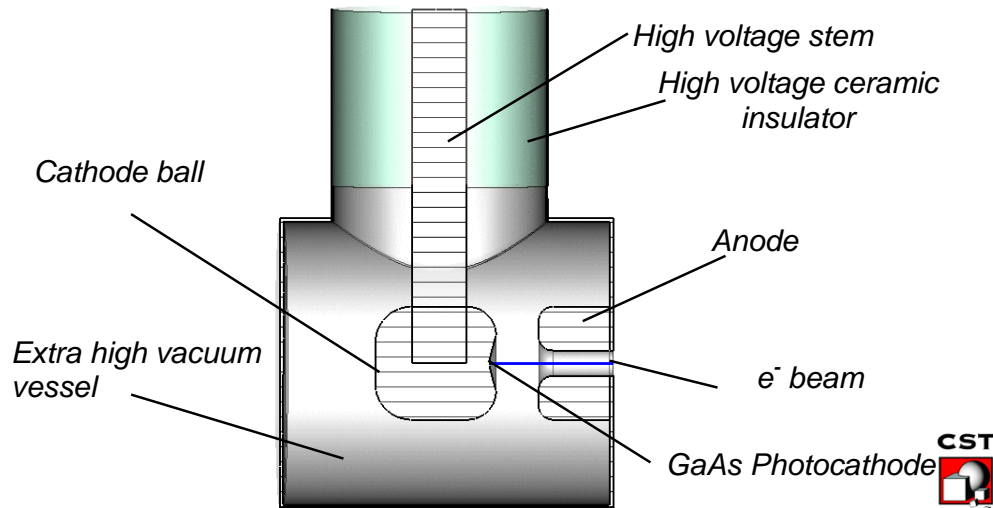
## 5. DC Electron Gun Design



Figure 4: Overview of the gun chamber as used for 3D electrostatic modelling.

The design of the electron gun chamber has been carried out by performing electrostatic simulations using Poisson for the 2D axially-symmetric case and CST Particle Studio for a full 3D simulation (Fig. 4). The two factors that need to be taken into account in designing the gun is the electric field strength on the metal surfaces, and how the electrode configuration affects the dynamics of the electron beam. The basic size of the cathode ball and the gun chamber were determined by trying to limit the electric field strength to less than 10 MV/m at the cathode surface, at the nominal voltage of 500 kV. To reduce the field on the cathode it is necessary to have a large radius of curvature on the edges, thus producing a "ball"-shape. Thus one has to compromise between a large cathode ball to accommodate a highly curved surface, and a desire to keep the overall size down. Various anode shapes were investigated with the important characteristic being the cathode-anode gap. This affects both the field strength and the dynamics of the beam. Figs. 5 and 6 show the results of the 3D electrostatic simulations. As can be seen, the maximum field slightly exceeds the aim of 10 MV/m on the curved surface of the cathode ball.
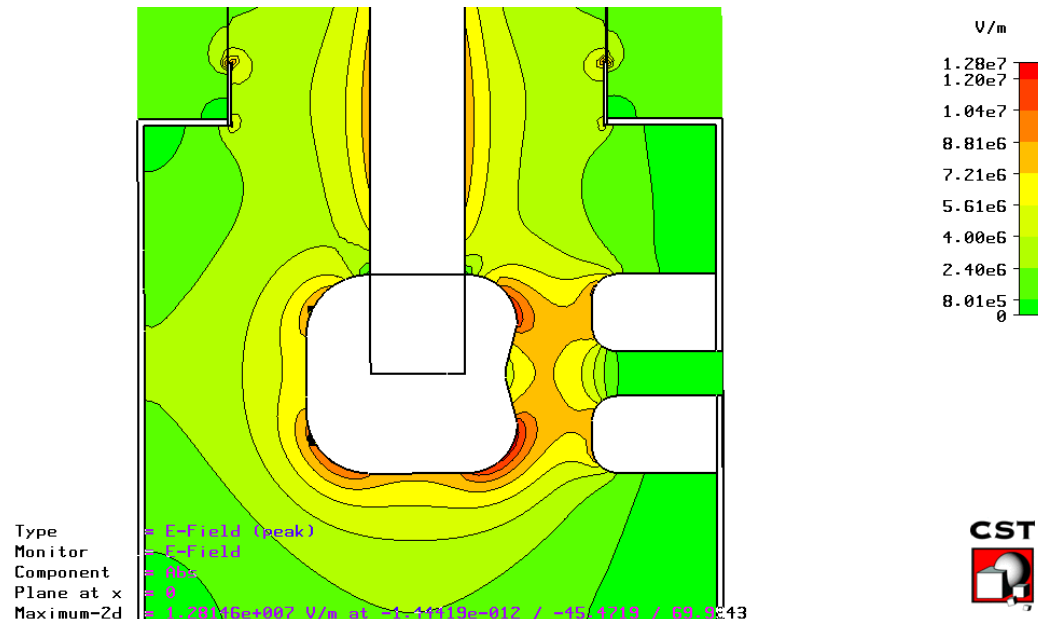


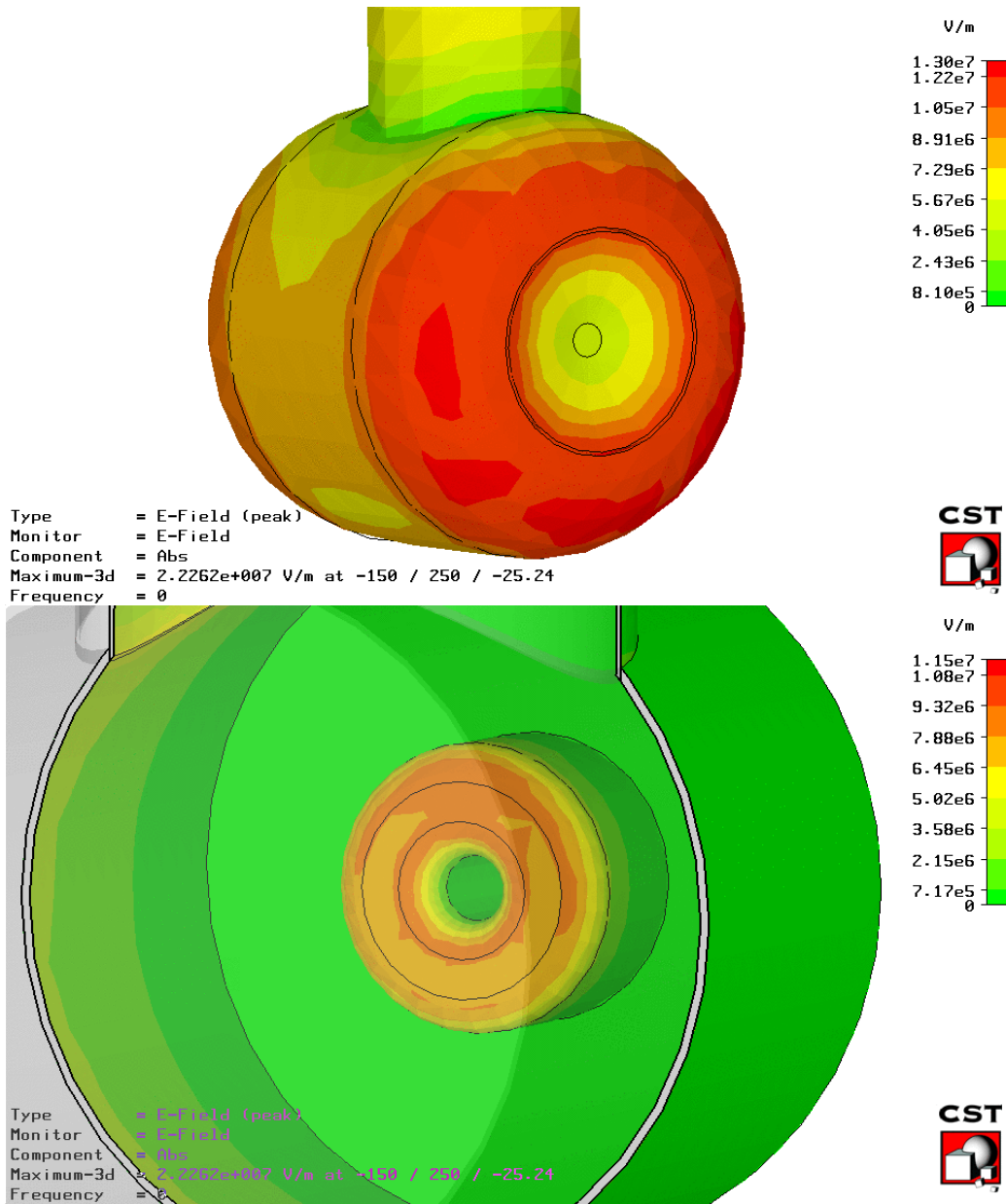Figure 5: Electric field in the gun chamber at 500 keV.

Figure 6: Electric fields on the surface of the cathode ball (top) and anode (bottom) at 500 keV.

It is planned to have a titanium anode and a molybdenum cathode, as these electrode materials have been observed to exhibit very low field emission [8]. The GaAs wafer is planned to be 12 mm in diameter to allow a laser spot of diameter 6 mm to be operated off-axis - if required - to reduce cathode degradation due to ion back-bombardment, which is at a maximum on-axis. The laser spot size was chosen as a compromise between a small spot for low emittance, and a large spot to improve cathode lifetime by spreading out damage from ion back-bombardment [9].

Fig. 7 shows the longitudinal and transverse electric fields along the beam axis of the electron gun. A transverse electric field is produced because the vertical cathode stem introduces an asymmetry. As this field is two orders-of-magnitude less than that of the accelerating field, its effects are taken to be minimal and have been neglected in the 2D beam tracking of section 6.
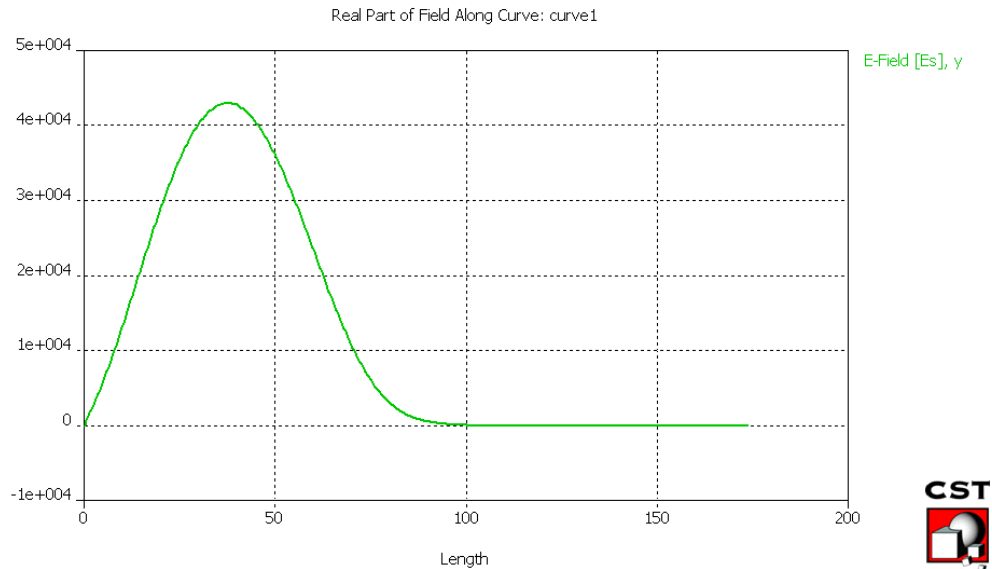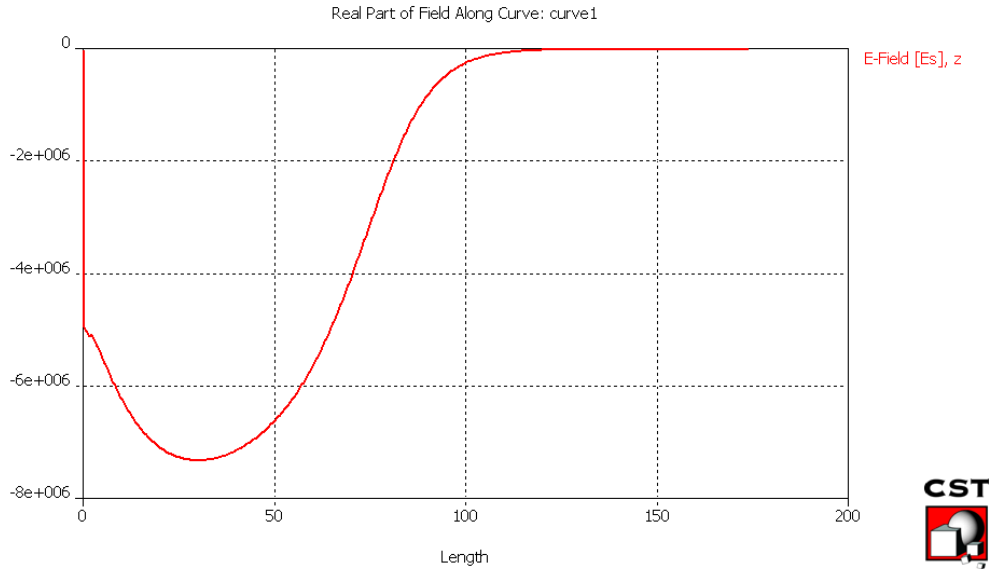
Figure 7: Longitudinal (top) and transverse (bottom) electric fields along the axis of the electron beam in V/m.

Upon creation, the electron bunch starts to diverge due to the effects of space charge. Therefore to keep the beam size small, the cathode electrode can be shaped to focus the beam. This is achieved by withdrawing the cathode emitting surface from the edge of the ball, thus creating a cone around the photocathode. The angle of this cone was optimised by modelling the gun chamber in Poisson, and then using the on-axis longitudinal electric field as input for Astra. Astra was used to track the beam from the cathode through a drift space of 1 m. Fig. 8 shows the normalised transverse emittance and spot size of the beam at 1 m for guns of differing focussing angle. Fig. 9 shows the emittance and spot size as a function of distance from the cathode for the gun with the photocathode withdrawn by 9 mm. This gun was chosen for the simulations of the whole injector because although the 10 and 11 mm guns provide a greater focussing, the emittance reaches a minimum and is already increasing before the beam reached 1 m.
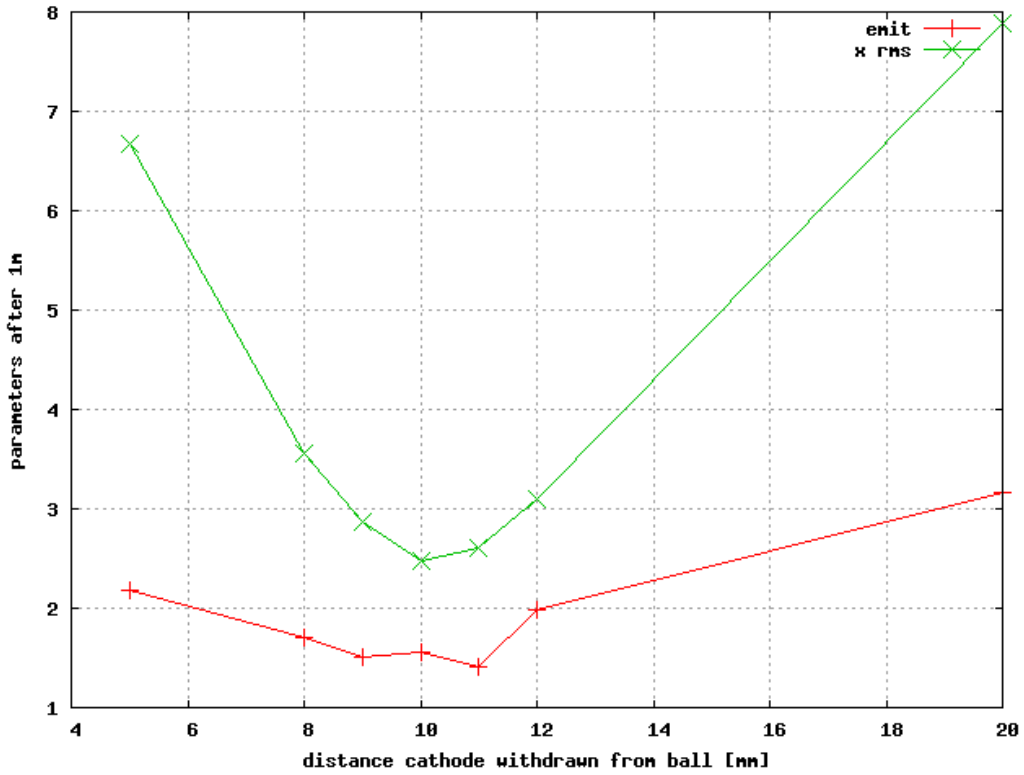
Figure 8: Normalised transverse rms emittance and rms transverse spot size after 1 m for electron guns of varying electrode focussing angle.
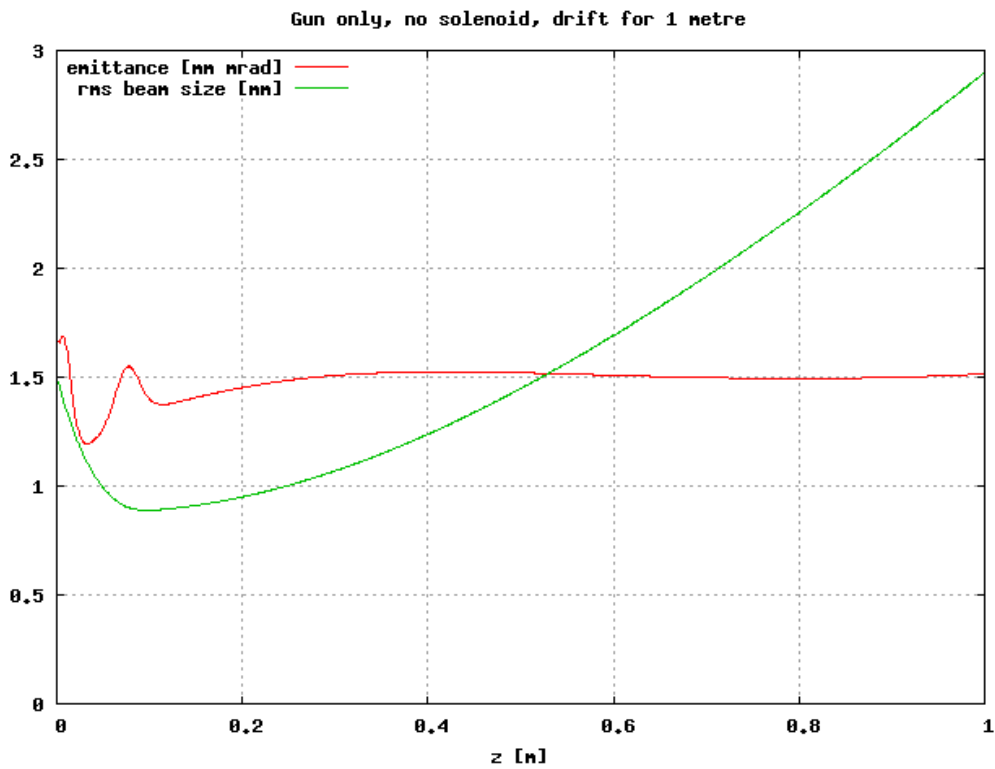


Figure 9: Emittance and spot size as a function of distance from the cathode for the gun with the photocathode withdrawn by 9 mm.

## 6. Injector Modelling

Beam dynamic simulations from the cathode up to the exit of the second SRF booster were performed using ASTRA [10]. The electron beam from the cathode was modelled transversely with a 6 mm diameter "top-hat" profile and longitudinally with a 20 ps rms Gaussian. The 6 mm spot size matches the laser and was chosen as a compromise between a small spot for low emittance, and a large spot to improve cathode lifetime by spreading out damage from ion back-bombardment [9]. There is adequate room on the 12 mm GaAs wafer to position the laser spot itself off-axis to minimise the ion back-bombardment damage further. An initial energy spread of 200 meV was included in the modelling that gives a thermal emittance of $0.94\ \pi\cdot\text{mm}\cdot\text{mrad}$ for the chosen spot size. The initial beam size was chosen to encompass all possibilities since the laser profile and cathode dimensions have not been finalised, and since the time response of the photocathode is not known.
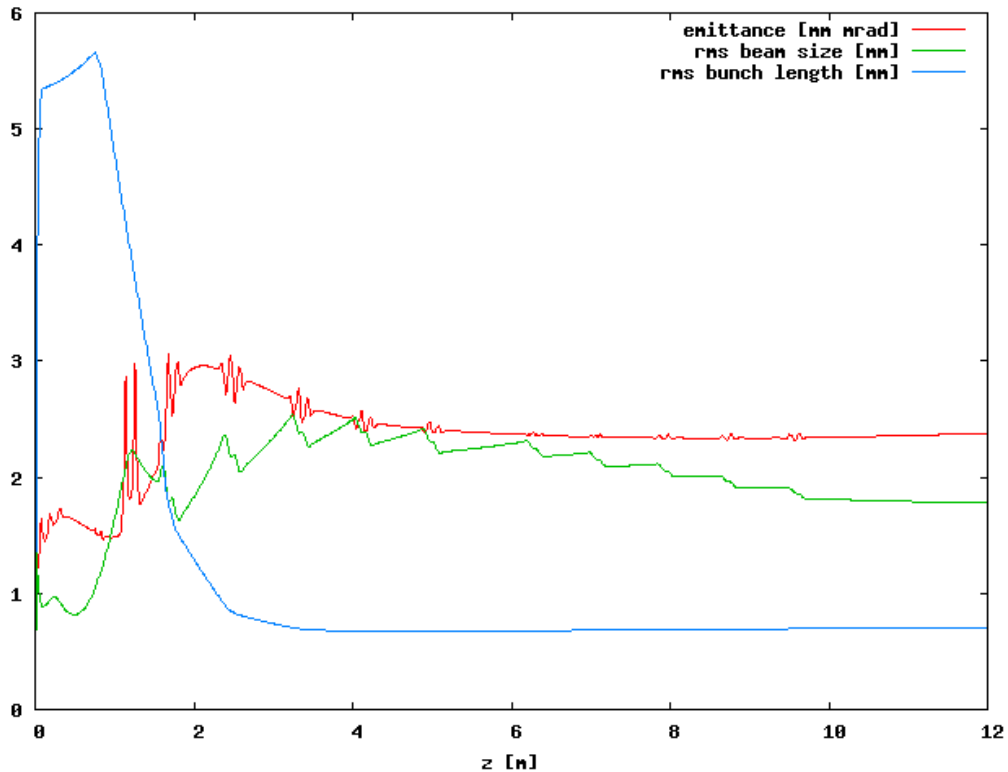


Figure 5: Beam parameters as a function of distance along the injector.

The injector layout was designed to minimise the length whilst leaving enough room for diagnostic placement. The first solenoid field strength was set to produce a minimum of spot size to pass through the buncher aperture and to maintain a transverse emittance lower than $2\ \pi\cdot\text{mm}\cdot\text{mrad}$ up to the first booster cavity. The main problem with the injector optimisation is simultaneously achieving a small emittance along with a bunch length as low as 2 ps. It was found that it was not possible to reduce the bunch length from 20 ps to 2 ps with the buncher cavity only. Emittance of the short bunch blows up at the entrance to the booster. The buncher has been set to reduce the bunch length down to 6 ps at the booster entrance; however this still causes an emittance growth of $\sim\!1\ \pi\cdot\text{mm}\cdot\text{mrad}$. The first superconducting cavity has been set to a negative phase to provide the final bunching from 6 ps to 2 ps. With the current values of solenoid and buncher field strength, adjusting the phase and gradient beyond the 2nd cavity produces no improvement in either emittance or bunch length. As such the parameters of these cavities have simply been adjusted to allow the final energy of 10.5 MeV to be reached. Fig. 11 shows the evolution of the beam parameters along the injection line and

Table 1 summarises them at the exit of the injector. Figure 12 shows the final beam distribution at the exit of the injector.

| Transverse emittance [π·mm·mrad] | 2.379 |
|---|---|
| Bunch length [ps] | 2.348 |
| Long emittance [π·keV·mm] | 9.747 |
| Energy spread [%] | 0.228 |

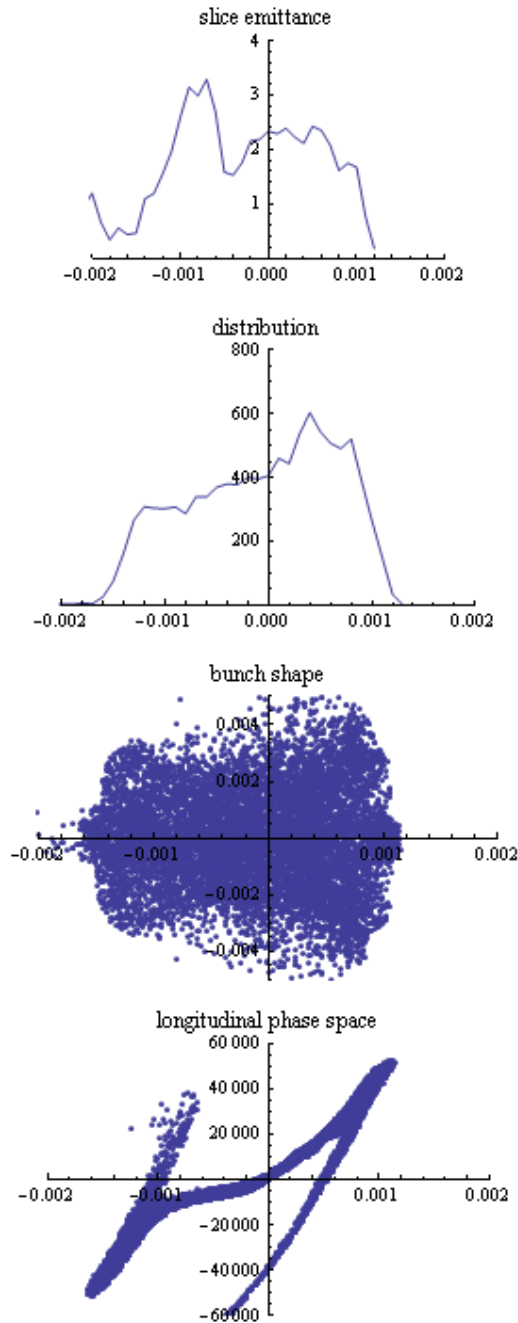Table 1: Beam parameters at the end of the injector.



Figure 6: Transverse slice emittance [mm mrad], number of particles [a.u.], transverse distance [m] and longitudinal momentum [eV/c] against distribution in time [ns] at the injector exit.

## 7. Jitter Studies

The drive laser of the photoinjector has to be synchronised to the RF feeding the bunching and accelerating modules to ensure correct phasing. Any timing jitter of the photoinjector laser will cause the electron bunch to see a different RF phase than that intended. To investigate what level of laser stability would still provide a good quality electron beam at the end of the injector, Astra simulations were carried out with delays in the arrival of the laser pulse from $\pm$ 0.1 to 10 ps investigated. It was found that the beam parameters varied almost linearly with jitter values between $\pm$ 1 ps, but beyond this varied wildly as shown in Fig. 13. Table 2 shows the percentage change in the beam parameters from that of the design system for laser timing arrival of 0.1 and 1 ps. The changes of up to 5 % show that a laser with stability up to 1 ps is acceptable for operation in this injector.

| Time delay | Energy | Transverse emittance | Transverse beam size | Bunch length | Energy spread | Longitudinal emittance |
|------------|--------|---------------------|---------------------|--------------|---------------|------------------------|
| 100 fs | 0.01% | 0.11% | 0.64% | 0.59% | 0.31% | 0.39% |
| 1 ps | 0.05% | 1.05% | 3.46% | 5.13% | 1.52% | 2.53% |

Table 2: Percentage changes of beam parameters from perfectly synchronised drive laser and RF for time delays of 100 fs and 1 ps.
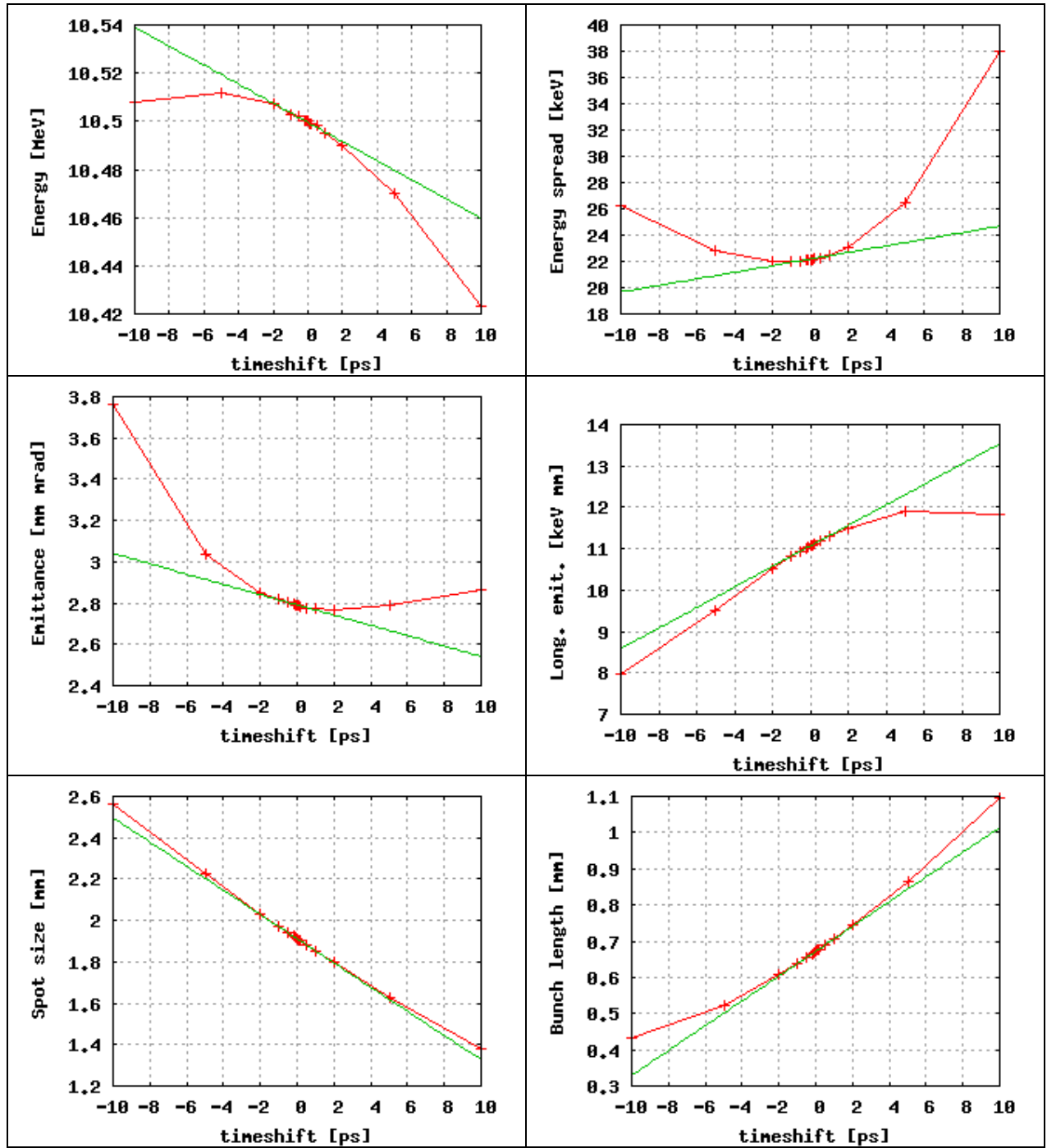
Figure 13: Effect of jitter timeshift on photoinjector parameters.

## 8. Summary

The design of an injector capable of providing a 77 pC electron beam at 10 MeV energy has been presented based on a 500 keV GaAs DC electron gun followed up with superconducting linacs. Simulations show a bunch length around 2 ps and emittance under 2.5 $\pi$·mm·mrad is achievable and the system should be stable for laser jitter of up to 1 ps. To achieve an average current of 100 mA, new photocathode structures are under development and the gun should be equipped with a multi-chamber preparation system. 3D electrostatic simulations have been carried out to design a gun capable of delivering a low emittance beam at 500 keV.

## References

[1] "4GLS Conceptual Design Report", CCLRC Daresbury Laboratory (2006), available at www.4gls.ac.uk.
[2] P.H. Williams et al, "Electron Beam Dynamics in 4GLS", PAC'07.
[3] V. Veshcherevich and S. Belomestnykh, "Buncher Cavity for ERL", PAC'03.
[4] V. Medjidzade et al, "Design of the CW Cornell ERL Injector Cryomodule", PAC'05
[6] P. Hartmann et al, "A diffusion model for picosecond electron bunches from negative electron affinity GaAs photocathodes", J. Appl. Phys. 86 (1999) 2245-2249.
[7] K. Aulenbacher et al, "Pulse response of thin III/V semiconductor photocathodes", J. Appl. Phys. 92 (2002) 7536-7543.
[8] F. Furuta et al, "Reduction of field emission dark current for high-field gradient electron gun by using a molybdenum cathode and titanium anode", NIM A, 538 (2005) 33-44.
[9] J. Grames et al, "Measurements of Photocathode Operational Lifetime at Beam Currents up to 10 mA using an Improved DC High Voltage GaAs Photogun", SPIN'06
[10] K. Flöttmann, ASTRA homepage, http://www.desy.de/~mpyflo/