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RE-OPTIMISATION OF THE ALICE GUN UPGRADE DESIGN FOR THE 500-pC BUNCH CHARGE REQUIREMENTS OF PERLE

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Abstract

The injector for PERLE, a planned ERL test facility, must be capable of delivering 500 pC bunches at a repetition rate of 40.1 MHz to provide a beam with 20 mA average current with a projected rms emittance of less than 6 mm·mrad. This must be achieved at two different operational voltages 350 kV and 220 kV for unpolarised and polarised operation respectively. The PERLE injector will be based on an upgrade of a DC photocathode electron gun operated previously at ALICE ERL at Daresbury. The upgrade will add a load lock system for photocathode interchange. This paper presents the results of a re-optimisation of the electrode system as ALICE operated with a bunch charge of around 80 pC while PERLE needs a bunch charge of 500 pC. This re-optimisation was done using the many-objective genetic algorithm NSGAIII to minimise both the slice emittance and transverse beam size for both required operational voltages.

INTRODUCTION

PERLE is a proposed energy recovery linac intended as a test facility for the LHeC [1, 2]. PERLE will operate with both polarised and unpolarised electrons at 500 pC bunch charge. To achieve this PERLE will use a DC photocathode gun based injector. The unpolarised operation mode will use a voltage of 350 kV to reduce the space charge induced emittance growth. The polarised mode will use a lower voltage of 220 kV. As it is easier to perform the neccesary spin manipulations on lower energy electrons and to reduce electron stimulated desorption which produces residual gas which damages the sensitive GaAs based photocathode needed to produce polarised electrons.

The injector for PERLE will reuse the ALICE DC electron gun [3]. Previously an upgrade was designed for the ALICE gun [4]. A modified version of this upgrade will be performed prior to using the gun for PERLE. One of the modification to the upgrade will be to change the electrode shapes. This is neccesary due to PERLE's higher bunch charge and the need to operate the gun at two different voltages. A photocathode preparation facility and a load lock system will be added. This will reduce the downtime required for photocathode exchange by allowing photocathodes to be exchanged without breaking the gun vacuum. To mitigate the photocathode damage due to back ion bombardment and the reduction in cathode lifetime it causes an anode bias of +5 kV will be added [5].

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PHOTOCATHODES

The choice of photocathode for the PERLE injector is limited by the requirement for high repetition rate and sufficient bunch charge to deliver high average current. It is difficult to generate sufficient average laser power with UV light since existing commercial systems are typically limited to no more than 1-2 W. The most likely laser solution is a frequency doubled Nd:YAG laser giving 532 nm light or a frequency doubled Ti:Sapphire laser giving 400 nm light. Hence the selection is limited to those materials able to generate electrons in the visible range, typically GaAs or alkali antimonides. Both these materials are easily contaminated by residual gasses in the vacuum system and thus impose a requirement on the gun for ultra-high or even extreme high vacuum (UHV or XHV), which fortunately can be realistically achieved by a DC gun.

Alkali antimonide based photocathodes, whilst still requiring very good vacuum, are less demanding than GaAs photocathodes and thus are likely to give longer operational lifetimes before replacement. Caesium antimonide is perhaps the easiest to fabricate and has reported values of QE are around 4-5% at 532 nm wavelength, which should allow the necessary bunch charge to be obtained with a laser system that is available commercially at reasonable cost. Potassium caesium antimonide materials are harder to grow, particularly with ideal stoichiometry, but have improved QE of up to 12% [6], which is comparable to GaAs photocathodes at a similar wavelength. Cathode lifetimes will be dependent on the vacuum conditions, but would be expected to be at least a week and possibly more for either Cs_3Sb or K_2CsSb. STFC have a plan to work on these materials based on a new deposition chamber that is currently under construction at Daresbury Laboratory (Fig. 1). The current plan envisages commencing work with the simpler Cs_3Sb material and then moving on to K_2CsSb.

If it would be desirable to operate PERLE with spin-polarised electron beam then it would be necessary to use GaAs based photocathodes as the only practical solution at the current time. The ALICE injector used GaAs photocathodes throughout its working lifetime and hence there is considerable knowledge within STFC on the preparation and use of this type of photocathode [7]. In the ALICE

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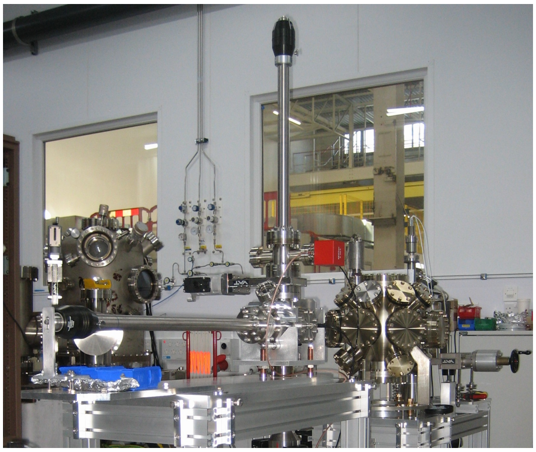

Figure 1: Alkali growth chamber under construction at Daresbury.

gun GaAs wafers with high Zn doping were used, but to obtain spin-polarised electrons the substrate would need to be replaced with one having lattice mismatch to provide a strained active layer, which gives rise to separation between the sub-bands of different polarisation. In addition, a 800 nm circularly polarised laser light should be employed to ensure only electrons from one sub-band are excited; this would also give rise to a significant reduction in QE to significantly less than 1%. GaAs photocathodes need to be activated by deposition of Cs and O to form a dipole layer, giving rise to a negative electron affinity. After degradation in performance during operation, the cathodes need to be re-activated. GaAs photocathodes would likely to have lower lifetimes than alkali antimonides, requiring re-preparation or replacement perhaps on a daily basis.

For the PERLE gun, it is proposed that an exchange system be implemented so that photocathodes can be changed without breaking vacuum. For GaAs photocathodes an existing design of photocathode preparation facility produced for ALICE could be easily implemented, but a new design would be required to deliver a system suitable for alkali antimonide photocathodes.

ELECTRON GUN RE-OPTIMISATION PROCEDURE

The PERLE electron gun electrode geometry must be a compromise design capable of operating effectively at two voltages. The electrode geometry, laser pulse spatial and temporal profile and the field in the first solenoid were optimised as a single system. The optimisation of the gun for operation at both 350 kV and at 220 kV is a four objective problem with four constraints. Each voltage having two objectives and two constraints. The two objectives are to minimise average slice emittance at the approximate position of the second solenoid and to minimise rms transverse beam size over the whole length of the beamline shown in Fig. 2. The two constraints are to keep the electrode surface electric field below 10 MV/m, to prevent field emission, and not to

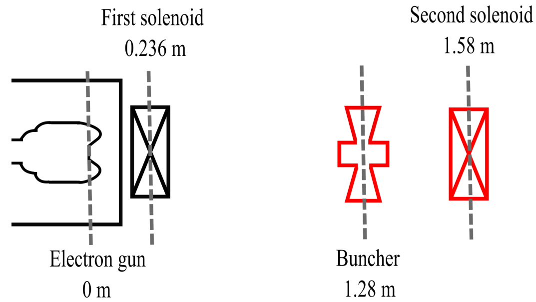

Figure 2: The layout of the start of the PERLE injector. The red elements were not modelled in the optimisation.

have particle losses. The optimisation of this four objective problem was done using the many objective optimisation algorithm NSGAIII [8, 9] as conventional multi objective optimisation algorithms tend to scale poorly beyond three objectives. DEAP [10] was used for the implementation of the algorithm. The algorithm parameters were set based on those used in the original paper [8], the number of reference points and the population size were set to 120. The optimisation was run for 65 generations.

Fitness Evaluation Procedure

Each evaluation of the fitness of a possible solution required one POISSON electrostatics simulation [11] and one ASTRA beam dynamics simulation [12] for each voltage. In the case that a simulation fails, for example due to an unphysical electrode geometry, a large constraint violation value is assigned to the individual causing those solutions to be removed from the population during the selection process.

The beginning of the PERLE injector beamline can be seen in Fig. 2 and consists of the electron gun followed by a focusing solenoid, a buncher cavity and then another solenoid. The positions are marked on Fig. 2 and were selected based on the lengths of the buncher cavity and the intermediate components in the ALICE injector. The gun electrodes and the first solenoid field were modelled. The buncher and second solenoid were not modelled in the simulation as finding appropriate settings for them requires consideration of the other parts of the injector. The simulation was ended at the midpoint of the second solenoid's position. The intial particle distribution for the 350 kV ASTRA simulation was created assuming a Cs_3Sb cathode and a 532 nm laser wavelength while the 220 kV simulation used an isotropic momentum distribution of 0.2 eV to represent the NEA GaAs based photocathode. The ASTRA simulations used a particle count of 4096 as a compromise between accuracy and run time.

Electrode Geometry Parameterisation

The same electrode shape must be used for both voltages as once machined it can't changed. During the optimisation the photocathode position is fixed due the pre-existing mechanical design of the interface between the gun and the photocathode exchange system. A diagram of the electrode

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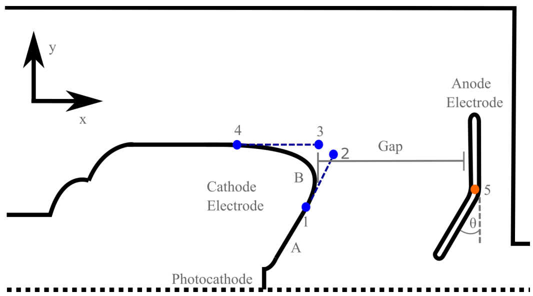

Figure 3: A sketch of the electrode parameterisation. The cathode control points are marked in blue. The dashed dark blue lines show when points are in line. The point where the angled section of the anode begins is marked in orange. The black dashed line is the axis of rotational symmetry.

parameterisation can be seen in Fig. 3. The cathode electrode shape is parameterized by 5 variables. It consists of a straight focusing section (section A) and a curved section (section B) joining section A to the side of the cathode electrode. Section A has fixed point near the photocathode and is parameterised by two variables, the coordinates of the other end of the section A where the section B begins (point 1). Section B is modeled as a cubic Bezier curve which has four control points [13]. In addition to the two variables which define the coordinates where section A ends and the section B begins the curve is parameterised by three additional variables. The second control point (point 2) is in line with the section A to ensure smooth continuity between the focusing plane and the rounded section of the cathode ball. One variable determines where along this line the control point lies. The other two control points (points 3 and 4) both have fixed y values at the edge of the cathode ball but their x positions can vary. This ensures that there is smooth continuity into the flat edge of the ball. For input into POISSON the Bezier curve was approximated by a series of circle arc sections.

The anode shape is composed of two straight sections at an angle to each other. This shape is parameterised using two variables the angle between the two sections (θ) and the radial position of the point where the two sections join (point 5).

RESULTS

Pareto Front

The result of the optimisation is a set of solutions which can be considered to be equivalently optimal but with different trade offs. From this set the prefered solution is selected. In Fig. 4 it is highlighted in orange. Visualising this four dimensional Pareto front is challenging. In Fig. 4 two of the pairs of objectives are plotted. This solution was chosen as a compromise but prioritising keeping the 220 kV transverse beam size small enough to pass through the apertures.

Selected Electron Gun

The selected solution was run again with 32768 particles to increase the accuracy. The more accurate run had

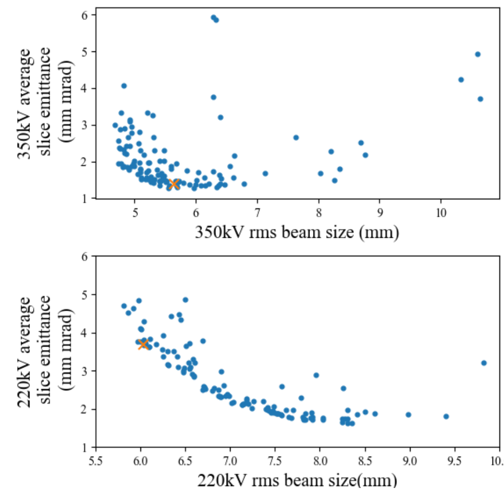

Figure 4: Plots of the objective values of the final solutions showing the average slice emittance against rms beam size for both of the operational voltages. The selected solution is marked as in orange. The x axis of the 220 kV plot is zoomed in for clarity but two solutions with large rms beam size are no longer visible.

a maximum transverse beam size of 5.6 mm rms and an average slice emittance of 1.1 mm·mrad at 350 kV. It also has a maximum transverse beam size of 6.1 mm rms and an average slice emittance of 4.1 mm·mrad at 220 kV. The selected electron gun geometry can be seen in Fig. 5.

The chosen solution has a focusing electron angle of around 7.3° significantly less than the 20° of the original design. This change keeps the photocathode surface field high at the lower voltage of 220 kV. The anode is moved slightly closer to the cathode electrode which will also increase the electric field at the photocathode surface.

CONCLUSION

The ALICE upgrade gun design has been re-optimised for the requirements of PERLE. Which are higher bunch charge and two different operational voltages. This re-otimisation was done using the many objective optimisation algorithm NSGAIII with the goal of minimising the slice emittance while still keeping the beam transversely small enough to pass through the apertures in the injector. A design was selected from the found Pareto front and this re-optimised gun will now be used in optimisations of the whole injector.

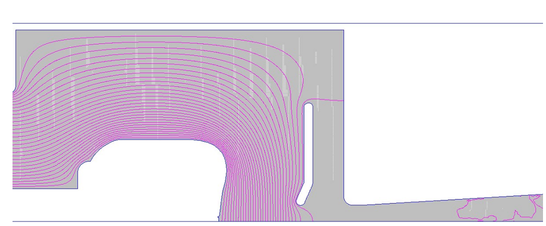

Figure 5: The geometry of the selected electron gun.

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