ELECTRON OPTICS, ELECTRON GUNS, ELECTRON BEAM EQUIPMENT, ELECTRON BEAM CHARACTERIZATION

Design of electron guns using a bespoke genetic algorithm

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Electron beams are used in many different industrial, medical and scientific applications. Each area has many specific requirements that can only be met with bespoke gun designs producing beams with the required intensity, brightness and divergence for the application. Usually, tentative gun designs are produced, simulated using modelling software and then the resultant beam is analysed in comparison to the requirements. The designer continues with this trial and error approach until a satisfactory design is derived. This is labour intensive and suffers and may not produce an optimum design. This paper describes the development of algorithms to automatically derive an optimum gun design. The method uses a genetic algorithm approach, where the gun design is described by a genetic code. Evolutionary processes are then applied to a population of gun designs, and after several generations near optimum designs are evolved. This offers a rapid method of customising gun designs and allows radical design approaches to be examined.

Проектиране на електронни пушки, използвайки разработен по поръчка генетичен алгоритъм (Колин Рибтон, София дел Позо, Вамадева Балачандран, Дейвид Райън Смит). *Електронни снопове се използват в много различни промишлени, медицински и научни приложения. Всяка област има много специфични изисквания, които могат да бъдат изпълнени само със специално конструирана електронна пушка за генериране на снопове с необходимата интензивност, яркост и възможности за прилагане. Обикновено ориентировъчен дизайн на електронната пушка се получава, чрез използване на симулационен софтуер за моделиране и след това полученият сноп се анализира и сравнява с изискванията. Дизайнерът продължава с опитите «проба-грешка», докато се получи задоволителен дизайн. Това е трудоемък процес и може да не се получи оптимален дизайн. Тази статия описва развитието на алгоритми за автоматично извличане на оптимална конструкция електронни пушки. Методът използва генетичен алгоритмичен подход, когато конструкцията на електронната пушка е описана с генетичния код. Тогава се прилагат еволюционни процеси за едно множество от дизайни на електронни пушки, и след няколко поколения дизайн, близък до оптималните дизайни еволюира. Това предлага бърз метод за персонализиране на дизайна на електронни пушки и позволява да бъдат изпитани радикални подходи за проектиране.*

Introduction

Electron beam guns are now been used for a wide variety of industrial processes where the beams generated carry out welding, texturing, material curing and most recently three-dimensional printing. Each process has specific requirements and constraints requiring in each case a bespoke electron beam gun design. This is usually being carried out by a trial and error process where the designer puts submits a tentative design to a computer simulation program which provides trajectory plots of the electron beam. Over the operating range of the gun, these trajectory plots can be compared with the beam requirements for the process and the suitability of the design can be assessed. Normally this would be an iterative process where the design is progressively modified to gradually improve the beam characteristics.

Trial and error design is necessary for electron guns as the geometry of a gun cannot be derived from the required beam trajectories. Within this work it is proposed that the design method can be automated by using meta-heuristic optimisation algorithms, where the gun geometry is treated as an input variable, and some quantified measure of the beam suitability is called the solution function. It should be noted that each call to the solution function requires a gun geometry to be simulated and electron trajectories to be plotted and then analysed against the process requirements. The time that this call takes is of course very dependent on the software and hardware used, but within this work typically this computation takes about 1 minute.

Optimisation algorithms could adjust multiple input variables that describe the gun geometry and examine the suitability of the solution function, which is a measure of the beam's fitness for purpose. There are many different types of algorithm available, and they are often inspired by natural processes. They include particle swarm optimisation, ant colony optimisation, simulated annealing and evolutionary algorithms. The most suitable optimisation method can be selected by considering its efficiency (i.e. the number of calls to the solution function), and its ability to find the optimum solution even in a problem space where there may be many local optima.

Within this work, an optimisation algorithm has been specifically developed for electron gun design and this has been applied to a new type of electron gun: an RF excited plasma cathode diode gun. An example is given of the application of an evolutionary genetic algorithm to the design of the plasma cathode electrodes. This design has been optimised for a material cutting application where the beam is required to be highly intense at short working distance.

Electron gun design

Electron gun analysis is carried out by calculating or simulating the electrostatic field in the gun. In the late 1940s and 1950s computing power for gun analysis was not available and estimates of the electrostatic field were made using physical models. However these have limitations particularly as the electrons themselves modify the electrostatic field - their mutual repulsion can cause significant deviation in their trajectories particularly when they are close to the cathode and are travelling at low velocity. This effect is generally referred to as space charge and it had to be taken into account for the higher currents electron guns that were developed for welding and melting applications. Pierce developed a calculated geometry to overcome space charge using a converging electrostatic field to cancel its effect [1].

During the 1960s electron optical software was developed for accelerator designs and this enabled even higher power guns to be developed with intense and parallel beams suitable for deep section welding, for example at Steigerwald, Sciaky and TWI.

There are now many electron optical analysis programs available. An example of one solution is shown in Figure 1. The progressive improvement in computing power that is readily available has reduced the computation time required by at least two orders of magnitude. This makes viable the use of optimisation algorithms, which necessarily require many electron optical solutions to be computed.

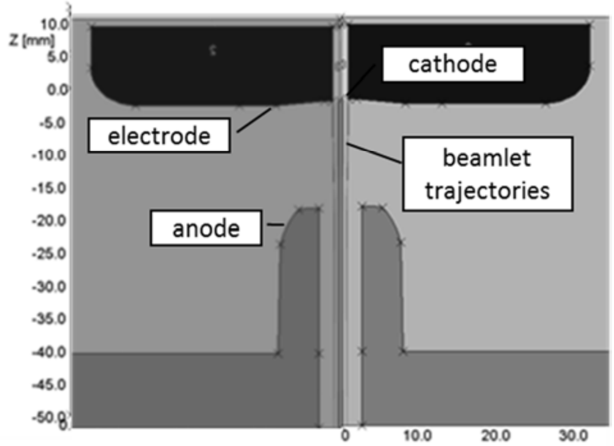

Fig. 1. Example of a 2D solution of an electron gun showing the geometry in cross section and the electron beamlet trajectories

1. RF plasma cathode diode gun

Even though thermionic cathodes are the most commonly used electron source in electron guns, plasma cathodes bring extra advantages that make them attractive over conventional electron guns [2].

A plasma cathode gun system consists of two main parts: a plasma chamber (plasma cathode) and an electron extraction/acceleration stage. The current density of the electron beam generated will depend on the plasma parameters such as density and temperature and on the electric field of the extractor/accelerator [3]. Thus, both parts of the system should be studied to optimise the electron gun system and maximise electron beam power.

Plasma chamber

Figure 2 shows a simplified diagram of a plasma cathode electron source. The configuration of the electrodes depends upon the electrical coupling method - for CCP the electrodes are within the plasma chamber. Once the gas is fed at low pressure in the plasma chamber, a plasma is generated by applying an electrical signal. The electrons break away from the atoms and start moving freely together with the other species in the plasma chamber, mainly neutral atoms (grey), positive ions (blue). Depending on the electron beam requirements, different ways to excite the plasma can be used: vacuum arcs, constricted gaseous arcs, hollow cathode glows, penning discharges and magnetron discharges [3]. The cathode consists of a low-pressure and low-temperature plasma. A typical pressure in the plasma chamber is 10^{-2} mbar.

Electron acceleration

Just as with conventional electron guns, a high voltage is applied between the cathode and the anode (at ground potential, 0V in the diagram). The high voltage electric field accelerates the electrons towards the anode and makes them into a beam. High electron beam powers can be achieved, so that the electron beams generated from plasma cathodes can be used for material processing applications. A typical pressure in the electron acceleration region of a plasma gun is < 10^{-3} mbar.

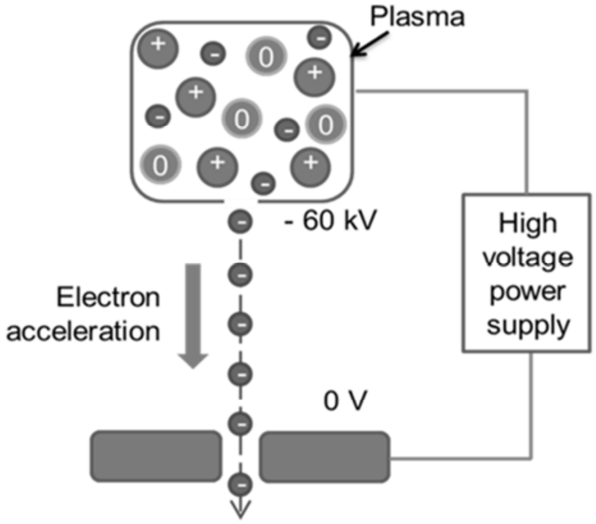

Fig. 2. Plasma cathode electron beam source

The plasma chamber geometry influences the electron beam characteristics. Low pressures in the plasma chamber are usually employed in order to avoid gas leakage into the acceleration gap that could cause high voltage breakdown. For capacitively coupled plasmas, long electrode gaps are then required, as dictated by Paschen's law. Typical values in a plasma cathode gun are less than 0.1 mbar gas pressure for electrode gaps in the order or higher than 0.1 m [4].

Hollow cathodes are commonly used in the plasma discharge chamber to improve the efficiency of electron densities. Hollow cathodes can be used in DC discharges as well as in RF discharges.

The EB current is emitted from an aperture at the side of the plasma chamber facing the acceleration gap. The EB current emitted from the plasma cathode is usually a fraction of the discharge current, thus high discharge currents will be needed to obtain high EB currents [4]. High current EBs are desired in the material processing applications of the RF plasma cathode gun that is concerned in this work. The aperture has an emission current density, similar to or greater than a thermionic cathode [3].

2. Plasma cathode advantages

Cathode lifetime and consistency

In conventional guns, cathode lifetime is limited due to material evaporation [5, 6, 7] and erosion. Erosion is mainly caused by ion bombardment when the beam is thermally processing material [8, 2]. As the cathode is gradually wearing from the beginning to the end of its life, this changes the beam characteristics (e.g. intensity and focus position) and introduces quality degradation to the processing. This leads to inconsistencies in the material processing, such as welding, cutting or additive manufacturing.

Plasma cathodes avoid problems caused by cathode wearing as the electrons are extracted from an ionised gas instead of an emissive surface. This allows the EB parameters to be stable over a long time [9] giving improved reproducibility compared to thermionic guns [4].

Operation in coarse vacuum

Plasma cathode electron sources allow generation of electron beams (continuous and pulsed) in coarse vacuum pressures, e.g. 0.01 to 1 mbar, which widens the number of applications and possibilities of electron guns [10]. High voltage and currents can be obtained in a low vacuum of the order of 10^{-3} mbar [11], instead of the 10^{-5} to 10^{-6} mbar pressure required for thermionic guns to prevent chemical degradation of the hot cathode. However, there are still limitations on the vacuum level for operating the gun to avoid high voltage breakdown in the acceleration gap.

No need for grid electrode

A grid cup electrode is used in triode guns to control beam power, however it changes beam shape over the power range and introduces beam aberration. Plasma cathode electron guns do not require a third electrode for controlling the beam power, avoiding this aberration. They can be operated as diodes where the beam power is controlled by the plasma parameters. This allows generation of both focused beams with high power densities and large cross section beams at high currents [4].

Beam pulsing

In thermionic guns the beam can only be pulsed slowly due to the thermal inertia of the cathode [2]. In diode guns pulsing is of the order of 100 ms whereas in triode guns beam pulsing requires complex electronics for control of the grid electrode voltage and pulsing transition times below 1 ms are not generally available in material processing applications.

The plasma parameters can be rapidly modulated - allowing the plasma diode gun to rapidly change the beam current. RF excited plasma cathode guns [12], like the design investigated in this work, allow rapid beam pulsing (below 1 µs) without the requirement of complex and expensive electronics.

3. Plasma cathode disadvantages

Electron temperature in plasma cathodes

Electrons from thermionic cathodes are at a lower temperature than plasma cathode electrons [3]. In low pressure plasma discharges, electrons may be at temperatures higher than 3-5 eV. This affects directly the thermal velocity spread of the EB and as a result will limit the beam brightness to a lower level with plasma electron emitters compared to thermionic emitters. Thus, there are limitations in the electron current density of focused beams, however this can be compensated by higher emissivity of plasmas compared to thermionic cathodes [3].

In addition to this, electrons from plasma emitters have higher mobility and are emitted from an emission boundary that varies. This may lead to differences in the electron optics design as the plasma parameters vary over the beam current range.

Optimisation algorithm

1. Genetic algorithm

A number of approaches have been taken by workers in the field to automatic electron gun optimisation. Optimisation of cathode curvature in electron guns has been previously carried out [13]. This method may be extended to look at the gun geometry as well as the cathode. However, this is a large and complex problem space and computing times with present technology may not make this tenable. Response surface modelling techniques have also been used. These have been shown to be very useful where the problem space is constrained and there is a single local optimum with a continuously variable solution function - for example optimisation of magnetic pole shapes for beam deflection. It is not expected that this optimisation technique would be effective for unconstrained problems, which are likely to have multiple optima and a discontinuous solution function.

Most recently [14] evolutionary algorithms have been shown to be effective for the design of a magnetron injection gun. In this case, the electron velocity spread was an important criteria for the design, and this was used as the solution function for the evolutionary algorithm.

A genetic algorithm can be formally stated as follows. The function:

$$f(x)\colon \Phi_g \to \mathbb{R}$$

assigns real values to genes, where Φ_g represents the genotypic search space. The optimal solution $\hat{x}$ is found from:

$$\hat{x} = \max_{x \in \Phi_g} f(x)$$

where *f(x)* is the solution function to be maximised [15].

A genetic algorithm can be implemented with the following steps. The electron gun design must be encoded to form a gene which entirely describes the electrode geometry. Initially, a population of randomly generated designs is created. Each of these is analysed by calling the solution function and is given a score. The highest scoring designs are selected and the lower scoring designs are discarded. The selected group then undergoes genetic processes such as random mutation and gene swapping. Gene swapping will cause geometric features from two of the high scoring parent designs to be blended into an offspring design. Mutation will occasionally cause variation in geometric features. The genetic processes are carried out to produces a new population. The process then repeats with a call to the solution function for each offspring member of the population, scoring, selection and genetic processes to give the new generation. As the score is a quantified measure of the suitability of the design for the application, once a member of the population achieves a score beyond a preset threshold the design process is deemed complete.

The algorithm has been adapted to be suitable for use in the design of electron guns in the manner described in the next section.

2. *Genetic algorithm specially adapted for electron gun design*

The following special adaptations were carried out to the genetic optimisation algorithm:

i. Genes were divided into those that can be mutated and swapped and a static template gene set for parts of the design that are totally constrained. This allowed all or part of a gun design to be evolved, for example to ensure that the design was mechanically compatible with existing fixturing;

ii. For each geometry parameter (vector coordinate or line curvature) a high and low constraint was recorded. This ensures that the final solution was within geometric bounds, for example to enable the solution to fit within an existing envelope. If the gene was mutated, the range of the mutation was in part set by the range of the geometry parameter - thus it provides a scaling factor for the mutation. Consequently, features that were highly constrained (e.g. near to the cathode) were mutated on a fine scale, whereas larger features had a greater degree of freedom and mutated over a wider scale;

iii. The geometry parameters were described in real numbers, as opposed to binary strings normally used in genetic code. This was to make a clear distinction between gene swapping (that only occurs between geometric parameters) and mutation (that affects the geometric parameter) and to ensure that the most efficient value for the important setting of mutation rate was implemented;

iv. The call to the solution function involved submitting a geometric model to a finite element solver for electron gun analysis. In this case the model was submitted using a list of commands that draw the geometry and define its boundary conditions, see for example Table 1. It was also possible to vary the boundary conditions in the gun so that the model can be solved for a range of operating points: acceleration voltages, bias voltages (in the case of triodes) and cathode temperatures (in the case of thermionic triodes). This ensures that the beam was explored over the operating range of the tentative design, rather than the beam produced at just one operating point;

Table 1

Example of geometric, description of part of an electrode in an electron gun

1	CARTESIAN YP=-38.7 CURVATURE=0 N=17 XP=7.95
2	CARTESIAN XP=100 N=93 YP=-38.7 CURVATURE=0.0
3	CARTESIAN YP=-50 N=12 F=NO XP=100.0 CURVATURE=0.0
4	CARTESIAN XP=2.75 N=98 YP=-50.0 CURVATURE=0.0
5	FINISH N=12 F=V
6	QUITDRAW
7	GROUP NAME=ANODE

v. The analysis software yielded a set of trajectories at each operating point examined. Further software was developed to derive beam characteristics from this trajectory set. The beam characteristics identified as important for material processing were:
   - Beam brightness;
   - Beam current in ratio to operating point conditions such as bias voltage or cathode temperature;
   - For a given lens position, the beam diameter measured as the full width at half maximum intensity, the full width of 50% of the beam current and the current weighted average diameter of the trajectories. The focused spot current distribution was also presented graphically see figs. 3 and 4;
   - The current weighted average trajectory angle and variance of this, as an indication of beam angle;
   - The current weighted trajectory source position and diameter, and variance of this, as an indication of the real or virtual primary crossover of the beam.

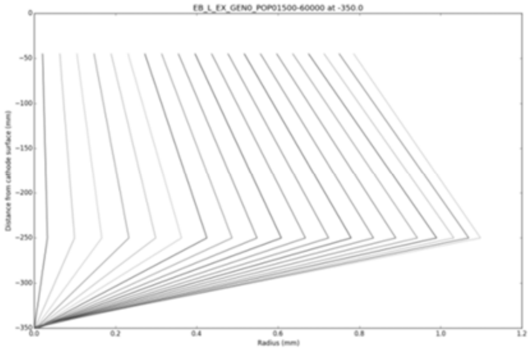

Fig. 3. Example of a ray diagram after projection of trajectories from the gun model through a mathematical lens to their focus at the work piece

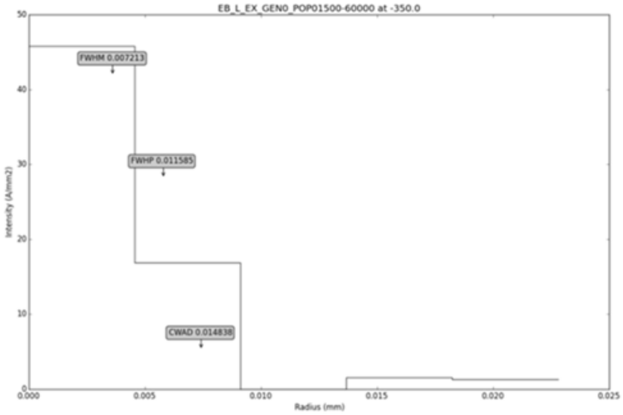

Fig. 4. Example of a beam intensity plot after projection of trajectories from the gun model through a mathematical lens to their focus at the work piece

vi. The final stage of the solution function was to derive a score for the design, based upon the suitability of the above beam characteristics for the application. The score could amalgamate or identify the maximum/minimum value over the operating points in the table, see Table 3 for the beam characterisation data generated at one operating point.

vii. Elitism was implemented - meaning that the parent designs were selected for the next generation parent group unless offspring designs scored more highly. Consequently, the best score in the population could never go down from one generation to the next, at worst it could stay the same.

viii. The genetic code contained a record of each designs ancestry to allow study of the evolutionary process for future improvements.

Table 2

Example of trajectory set from the analysis software

Current	X	Vx	Vz
-8.11E-05	3.00E-02	3.01E+07	-9.84E+10
-2.43E-04	9.23E-02	9.50E+07	-9.84E+10
-4.05E-04	1.56E-01	1.63E+08	-9.84E+10
-5.67E-04	2.21E-01	2.33E+08	-9.84E+10
-7.30E-04	2.87E-01	3.04E+08	-9.84E+10
-8.92E-04	3.51E-01	3.73E+08	-9.84E+10
-1.05E-03	4.14E-01	4.37E+08	-9.84E+10
-1.22E-03	4.73E-01	4.93E+08	-9.84E+10

Table 3

Example of beam characteristics derived from trajectory data

Cathode Temp. (K)	1450
Accel. Potential (V)	-30000
Beam Current (A)	-3.54E-03
Source Position (mm)	4.03E+02
Variance (Zsrc)	3.62E+03
Source Radius (mm)	-6.08E-02
Beam Angle at Focus (str)	1.77E-05
Brightness (A/mm^2/str)	-4.30E+03
Lens Focal Length (mm)	8.67E+01
D-Imean (mm)	1.86E-02
FWHM (mm)	8.24E-03
FWHP (mm)	1.60E-02

Electrode evolution

The process described in the previous section has been applied to the RF excited plasma cathode gun geometry and the anode geometry is given as an example. For an electron beam cutting application, the required beam was intense at focus, but also of low angle to pass through a narrow bore lens in the proposed system. These points towards a high brightness beam and the requirements are summarised in Table 4.

Table 4

RF plasma gun beam requirements

Metric	**Requirement**
Diameter at 150 mm from cathode	Ideally 4 mm
Brightness	> 5000 Amm^{-2}sr^{-1}

It is necessary to combine several factors into a single score for the tentative design. This is achieved using weighting factors and capping the score contribution from some beam characteristics. The scoring is described in the following pseudo-code:

```
Over the cathode temperature range 1450 – 1600K
and for 30kV and 60kV accelerating potentials:
score = add Log(brightness)*beam current
If beam current <20mA
If 1/(beam diameter 150mm from cathode – 4) >10
Add 10
Else
add abs(1/(beam diameter 150mm from cathode – 4))
```

The evolutionary parameters used are critical to the efficiency of the optimisation algorithm. These were studied using an analogous problem - where a shape was to be optimised to fit a target shape. The solution function (to be minimised in this case) was the sum of the distance of each corner of the tentative shape to that of the objective shape. This could be solved very quickly allowing a study of the best evolutionary parameters for efficient optimisation. The analogous problem was similar to that of gun design, in that it is a shape with geometric parameters. However, the solution function is continuous with only one optimum which was dissimilar to gun design. From this study [13] the evolutionary parameters in Table 5 were selected.

Table 5

Evolutionary algorithm parameters

Parameter	Value
Parent group size	4
Offspring group size	6
Mutation scale	0.1
Mutation probability	0.07

The designs were named with a generation number (Gen_) and a population identifier (Pop_). Gen_0 designs were from the first, randomly generated population. A design named Gen_10_Pop_4 would be the 4th member of the 10th generation. The naming convention was also used to record each designs ancestry within the genetic code. The scores for each generation were logged and examples are given in Table 6a and 6b. As elitism was enabled the population for a generation was made up from the set number of offspring and then parents from previous generations that have scored highly enough to remain in the parent group.

The graph shows that there were incremental improvements in the best score for many generations and on one occasion a step improvement. The optimisation algorithm has been run several times with similar trends in the best score, where this occurs when both the characteristics amalgamated in the score are optimised simultaneously.

The optimisation was complete within 3 hours without any expert intervention, with each call to the solution function being complete within 4 minutes. This compares favourably with trial and error design that would take some 10 to 15 hours with frequent expert intervention.

Table 6a

1st generation population ranked scores

Model	Score
Gen_0_Pop_1	2.37
Gen_1_Pop_6	2.10
Gen_1_Pop_4	2.10
Gen_0_Pop_3	2.09
Gen_1_Pop_5	2.09
Gen_0_Pop_0	2.03
Gen_1_Pop_7	2.02
Gen_1_Pop_8	2.02
Gen_0_Pop_2	2.01
Gen_1_Pop_9	2.01

Table 6b

10th generation population ranked scores

Model	Score
Gen_10_Pop_4	11.59
Gen_6_Pop_4	3.57
Gen_8_Pop_6	3.57
Gen_9_Pop_5	3.57
Gen_10_Pop_6	3.57
Gen_10_Pop_7	3.57
Gen_9_Pop_7	3.23
Gen_10_Pop_5	3.03
Gen_10_Pop_8	2.89
Gen_10_Pop_9	2.65

The optimization algorithm progress was monitored by plotting the best score for each generation, see Fig. 5.

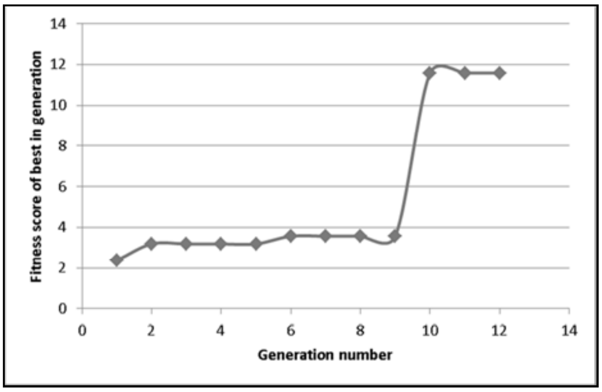

Fig. 5. The best fitness score in successive generations

Conclusions

From the work carried out the following conclusions can be drawn:

- A genetic algorithm has been developed suitable for the automatic optimisation of electron gun designs that generate specific electron beam characteristics;

- The algorithm has been used to design an electrode for a new RF excited cathode electron beam gun;
- The algorithm provides a fast and more efficient way to design electron guns.

Acknowledgements

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