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BEAM DYNAMIC ANALYSIS OF RF MODULATED ELECTRON BEAM PRODUCED BY GRIDDED THERMIONIC GUNS

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Abstract

A gridded thermionic cathode electron gun used widely in different types of particle accelerators such as circular, linear and energy recovery configurations was designed and modelled. The gun is based on the Pierce-type configuration. It was initially designed using the Vaughan synthesis following optimisation by a two-dimensional DC electron trajectory solver TRAK. After optimisation, the grid on the cathode was inserted and the RF field was introduced, which was then simulated using the particle-in-cell (PIC) code MAGIC. High duty cycle operation at frequencies, 1.5 GHz and 3.0 GHz, was investigated while exploring the relationship between the bunch charge and bunch length. The beam dynamics results from the PIC simulations showed that a minimum pulse length of 106 ps could be achieved with a bunch charge of 33 pC when the driving RF frequency was 1.5 GHz. Operating at a higher RF frequency did not significantly reduce the micro-pulse length. A normalised emittance of less than 15 mm·mrad for the entire electron pulse was demonstrated in the PIC simulations.

INTRODUCTION

Radiofrequency (RF) electron guns are basic components of linear particle accelerators (LINACs) which have a variety of applications in scientific research and industry. The development of high-current, low emittance and short-duration electron beam pulses from electron guns has been necessary for the operation of radiation sources such as Free Electron Lasers (FELs) [1-5] and as the electron source in medical LINACS [6].

There are different types of electron guns depending on their emission process from the cathode and their operation. The three main electron sources are thermionic cathodes, photocathodes and field emission cathodes. Thermionic cathodes [7-12] are very robust due to their long lifetimes which can reach up to 100,000 hours, however the energy spread and the long pulses at the exit of the LINAC are not ideal for certain applications. This problem is resolved by photocathodes [13-17] which can achieve high current densities, low emittance, short electron pulses although photocathodes require a high power laser and high vacuum to operate. Lastly, field emission cathodes [18, 19] are able to generate high current densities but are fragile and prone to damage due to vaporisation of the cathode tip. Another differentiation between electron guns is the type of beam modulation used which may be a high voltage modulated diode or a triode gun costing of a modulated anode in combination with an RF grid. In a normal diode electron gun, high voltage is applied between the cathode and the anode to create the electron beam. This type of gun limits the repetition rate as it takes a certain amount of time to switch on and off the high voltage power supply. In the triode electron gun configuration, the beam is modulated with an RF voltage applied to a grid located next to the cathode as well as a DC modulated voltage. Two types of modulation: a long pulse modulation and RF pulse modulation are used in the triode guns. The advantage of RF modulation over DC-like long pulse modulation is that microbunching structure of the beam at the exit of the gun can be achieved, which provides higher capture efficiency of the beam by the subsequent RF linear accelerator. Hence in the triode type electron gun, the current is controlled with a much smaller RF voltage which is capable of a much higher repetition rate.

For this paper, an electron gun was designed and modelled using Particle-In-Cell (PIC) simulations. The electron gun was based on a gridded thermionic cathode with a Pierce type configuration geometry with the specifications of the LINAC, dictating the minimum achievable pulse length to be established. Furthermore, the relationship between the bunch charge and bunch length along with the beam emittance was examined.

DESIGN OF THE ELECTRON GUN GEOMETRY

The initial electron beam parameters of the LINAC, which the gun is going to be used for are listed in Table 1. The study was to design a thermionic cathode RF gun to meet the required beam parameters, and also to investigate the properties of the electron bunch at the exit of the gun, including the bunch charge, bunch length and emittance. The initial electron gun geometry was generated based on the Vaughan synthesis [20] with 4 input parameters, including the beam voltage, beam current, emitter radius as well as the beam waist as shown in Table 1. The initial geometry was then used as the starting point for further optimisation to get more accurate simulation results and to further improve the electron beam quality, including good laminarity and a small emittance.

The beam trajectories of the optimised geometry simulated by TRAK are shown in Fig. 1(a). The acceleration voltage between the cathode and anode was 25 kV and the emitted current was 1.0 A. The radius of the beam waist was ~1.5 mm. This geometry was transferred

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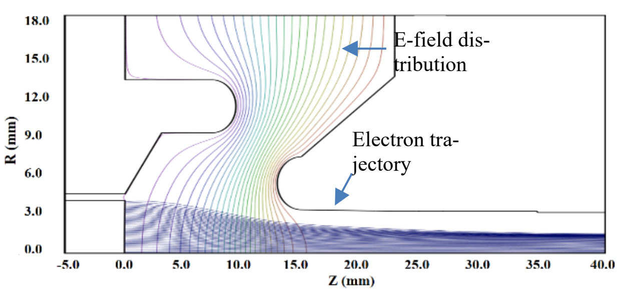
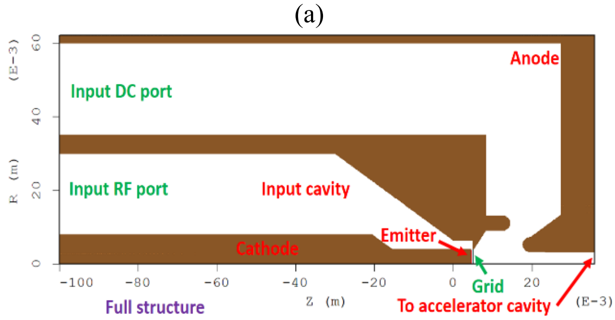
to the PIC code MAGIC as shown in Fig. 1(b) and a model was developed that allowed the electron gun to be simulated. When driven by an RF voltage and a bias voltage, an electron bunch was generated. Figure 2 shows the spatial distribution of electrons at different time frames, corresponding to the process of bunch emission from the cathode, bunch acceleration by the electric field and at the exit of the anode.

Table 1: Specifications of the LINAC

Parameter	
Beam energy, MeV	6
Linac RF frequency, GHz	3
Repetition rate, Hz	300
RF pulse length, µs	7.5
RF gated frequency, GHz	1.5 or 3.0
Bunch charge Q, pC	33.3 @ 1.5 GHz 16.7 @ 3.0 GHz
Bunch length τ, ps	As short as possible
Peak current, A	Q/τ
Pre-acceleration voltage, kV	25
Beam radius, mm	<2.5



(a)



(b)

Figure 1: The optimised geometry of the gun using (a) TRAK showing electron trajectories in blue and the coloured equipotential profiles and the transferred optimised geometry using (b) the PIC code MAGIC.

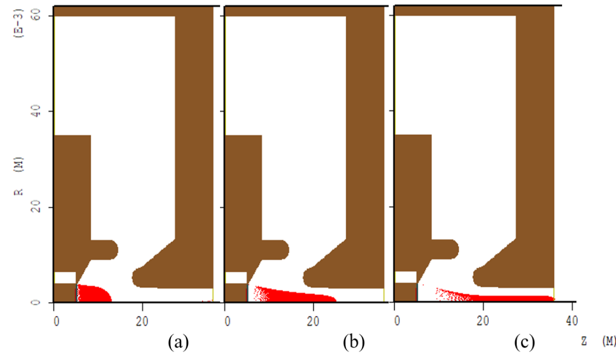


Figure 2: Different time frames showing the evolution of the beam bunching at the different regions (a) bunch emitted from the emitter, (b) bunch acceleration by the electric field, (c) bunch at the exit of the anode.

PERFORMANCE OF THE ELECTRON GUN MODEL

The performance of the RF gun was studied by applying different combinations of the RF and bias voltages on the grid where $U_{grid} = U_{rf} + U_{bias}$. The grid was located at 0.16 mm distance from the cathode. The waveform of the emitted current is shown in Fig. 3. The amplitude of the collected current pulse waveform of the emitted current was about 40% of the emitted current.

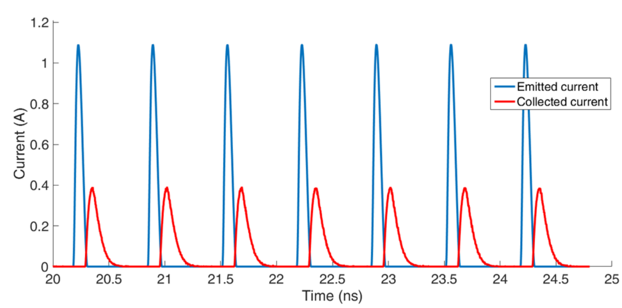


Figure 3: The emitted current from the cathode and the collected current at the exit of the anode.

The simulation results at different combinations of U_{rf} and U_{bias} at a driven frequency of 1.5 GHz is given in Fig. 4(a). By varying the RF and bias voltage, the bunch length and bunch charge of the collected current at the exit of the anode changed accordingly. The growing of the bunch charge as a function of bunch length follows a linear trend. For the requirement of the LINAC, the minimum bunch length which could be produced for a bunch charge of 33.3 pC was 106 ps. For a higher RF frequency of 3 GHz the results are shown in Fig. 4(b). In this case, a minimum bunch length of 100 ps could be achieved with a bunch charge of 16.7 pC, showing not much improvement on the bunch length when operating at this higher RF frequency.

The sliced transverse emittance was calculated by statistically counting the electrons at the exit of the anode. The sliced emittance along the current pulse is shown in Fig. 5. The two regions of the bunch, head and tail have different values of emittance. It can be seen the emittance was lower

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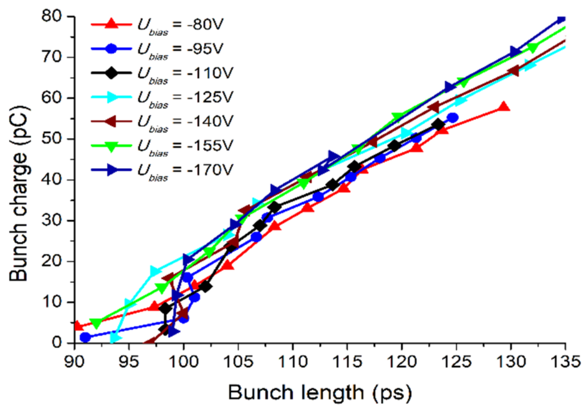
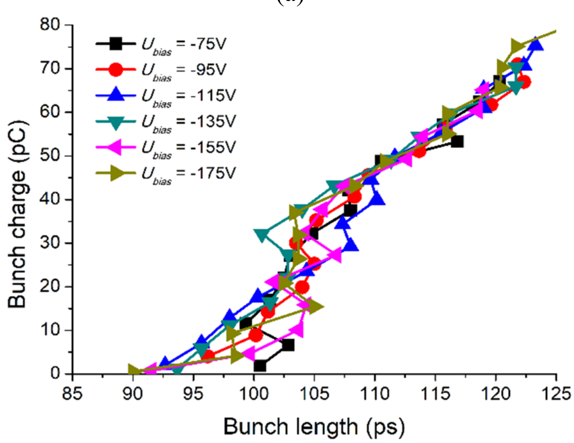
at the head of the bunch and larger at the tail. There were two types of emittance calculated. These were, the geometrical and the normalised emittance. The relationship between these two types of emittance is given by $\varepsilon_{norm} = \beta\gamma\varepsilon_{geometrical}$ where β and γ are the relativistic functions. The major part of the bunch corresponding to the peak in the current pulse had a normalised sliced emittance of less than 5.6 mm·mrad.



(a)



(b)

Figure 4: The relationship between the bunch length and bunch charge at different grid voltages with RF frequency of (a) 1.5 GHz and (b) 3.0 GHz.

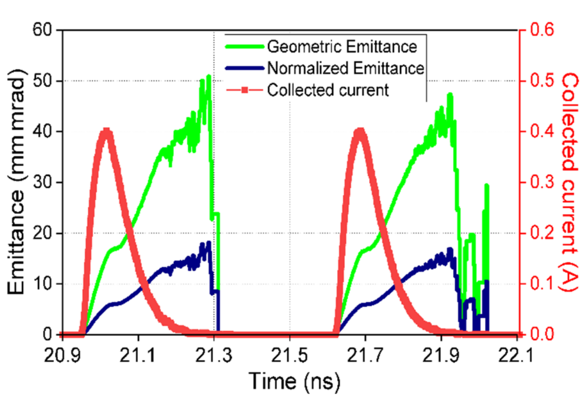


Figure 5: The emittance of the electron at the exit of the anode.

CONCLUSION

In this paper, a thermionic gridded electron gun for particle accelerator applications was investigated. The electron gun was based on the Pierce-type configuration and its geometry was optimized using TRAK. The performance of the electron gun was studied with PIC simulations which established the minimum achievable length of 106 ps for a bunch with a charge of 33.3 pC satisfying the requirements of the LINAC. The sliced transverse emittance was calculated by statistically counting the electrons at the exit of the anode resulting in a normalised emittance of about 5.6 mm·mrad at the peak of the current pulse.

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