

Flexi Electrode Electron Gun for Long Life Traveling-Wave Tubes

Abhay Shankar^{*}, Atmakuru Nagaraju, Amitavo R. Choudhury, and Sanjay K. Ghosh

Abstract—A flexi electron gun consists of multiple electrodes and can be used to maintain uniform beam current over the life of a traveling-wave tube (TWT). The flexi electron gun consists of dispenser cathode, anode1, anode2, and anode3 in addition to a beam focusing electrode (BFE). In an optimized electron gun, anode1 potential plays an important role in increasing beam current within the same biased condition of electronic power conditioner (EPC) and can be used as a critical parameter to increase current with time when cathode performance (beam current) degrades with time. Geometry, position, and bias of these electrodes with respect to cathode provide low perveance electron beam optics to the interaction structure of a TWT. The flexi gun has been modelled in EGUN, developed and integrated with TWT, and simulated results are compared with experiment. This paper presents a detailed investigation of the effect of anode1 on beam current and also presents the cause of large variation of simulated and measured beam currents through back simulation in EGUN.

1. INTRODUCTION

TWTs are simply unparalleled in the family of vacuum microwave tubes and solid-state power amplifiers (SSPAs) due to their unparalleled performances, namely, high frequency, wide bandwidth, high power, high gain, high efficiency, long life, reliability, etc. [1–3]. Performance and life of a TWT mainly depend on the beam optics, which further depends on the geometry and potential of the electrodes and cathode life. In fact, TWTs wear out due to exhaustion of cathode — performance (emission current density) degrades with time, and hence flexi TWTs would be a better choice for long life application. In a flexi TWT, the multi-electrodes of the electron gun will have flexibility to adjust electrode potentials, under the same biased condition, to increase electron beam current, which deteriorates with time due to exhaustion of cathode. In flexi electron gun, geometry, position, and potential of multiple electrodes, like, BFE, anode1, anode2, anode3 with respect to cathode are the key parameters in forming desired beam optics like conventional electron gun. For maximum beam current, BFE is kept at cathode potential, and any change in BFE potential decreases beam current. Anode2 keeps positive w.r.t cathode to protect cathode from the back bombardment of positive ions, and anode3 is at ground potential. However, anode1 plays an important role to control beam current, and increase in anode1 potential increases beam current linearly without affecting beam optics much. The change in anode1 potential in small steps changes beam current, and this change in potential perhaps can be done under the same EPC biased condition, that is, without affecting basing load. For long life condition or on-board satellite application, TWT needs to deliver constant performance over a long time. However, cathode performance or beam current decreases with time. Under such a condition the increase in anode1 potential through telecommands will increase beam current, and constant TWT performance can be achieved over time. Thus, the inclusion of anode1 and the flexibility of its potential variation makes flexible electron gun for long life application.

Received 6 January 2020, Accepted 14 May 2020, Scheduled 29 May 2020

^{*} Corresponding author: Abhay Shankar (abhayshankar196@gmail.com).
The authors are with the CSIR-CEERI, Pilani 333031, India.

Advanced systems are becoming more and more agile to state-of-the-art long life TWTs which are emphasized, and the electron gun plays a key role in improving the life of TWT. Pierce conventional electron gun geometry has undergone several evolutions around its basic configuration for state-of-the-art applications [4–7]. It is well known that TWTs wear out in many cases due to exhaustion of cathode, and hence for long life performance, cathodes are operated at lower temperature. Required beam optics is obtained under space charge limited condition with a set of suitably biased electrodes in the electron gun geometry. Due to the degradation of cathode with time beam current decreases affecting TWT performance, but long life TWT demands constant beam current over the entire journey of TWT. To make a trade-off between these two, designer needs to explore the way to maintain constant beam current over the life during exhaustion of cathode with time. This approach will be important when the TWTs are used in on-board satellite transponders. To maintain constant beam current during degradation of cathode performance, one can increase cathode power to increase beam current or to emit more electrons, which in turn enhances cathode exhaustion rate. Thus, to balance both, that is, uniform beam current and less cathode exhaustion over time, one needs to use flexi electron gun — flexibility in variation of anode potential without increasing cathode power. Change in anode potential in steps, in particular, anode1 potential, increases beam current and helps in maintaining constant beam current.

Thus, the electron gun for long life application needs to be modelled suitably for the required low perveance beam optics [8–10]. Beam optics of low perveance electron gun is sensitive to the geometry, position, and potential of the electrodes and is designed/synthesised using commercial software EGUN and achieved by suitable shaping the electrodes, namely, beam focusing electrode (BFE), anode1, anode2, anode3, etc. (Fig. 1). In a TWT, beam current decreases with time due to degradation of cathode, which can be recovered by suitably increasing anode1 voltage without affecting other electrode voltages, beam optics, and focusing scheme. In an optimized electron gun, the beam current increases with the increase in anode1 voltage in steps without deforming beam optics beyond sensitive zone [11–13]. However, in an optimized electron gun, with the increase in BFE voltage, beam current decreases; beam optics deforms; anode2 and anode3 have no significant effect on beam current but affect beam optics, and hence the potential of these electrodes is kept unaffected. Thus, to enhance the beam current with time, one may need flexi electron gun keeping the provision to increase anode1 voltage.

The modelled electron gun is developed and integrated with the TWT, and it has been observed that there is a huge variation of designed and measured beam currents. After back simulation in EGUN, it is observed that the variations of designed and measured currents are due to deficiency in engineering model. This paper presents the design and development of flexi electron gun for long life application, which may find potential application in on-board satellite applications.

2. APPROACH

2.1. Electrostatic Design of Electron Gun

The flexi electron gun consists of cathode, BFE, anode1, anode2, and anode3, and is modelled and designed in electrostatic solver EGUN (Fig. 1) to operate at -7 kV cathode voltage. Unlike conventional electron gun, this flexi gun consists of additional electrode anode1 between BFE and anode2. Equipotential lines and beam optics obtained from EGUN are shown in Fig. 2. EGUN is a commercial software, and the output gives following parameters as: geometry of the electron gun, electron beam trajectories, equipotential lines, magnetic circuit, axial magnetic field, cathode leakage magnetic flux, etc. Under space charge limited condition, the geometry and potential of electrodes control beam optics, and anode1 has better control on beam current.

Design/modelling steps are: i) beam parameters, namely, voltage, current, waist radius, and cathode emission current density, and initial estimation of gun geometrical parameters, namely, cathode disc radius, cathode spherical radius, anode aperture radius, anode spherical radius, cathode to electrodes distances (both radial and axial) (Fig. 1), etc. are obtained through synthesis of electron gun geometry [4, 5]; ii) synthesized geometry is then constructed and simulated in EGUN [14] and optimized through iterations. Anode1 regulates beam perveance, and the positive potential of anode2 with respect to anode3 protects the cathode surface from back ion bombardment [11].

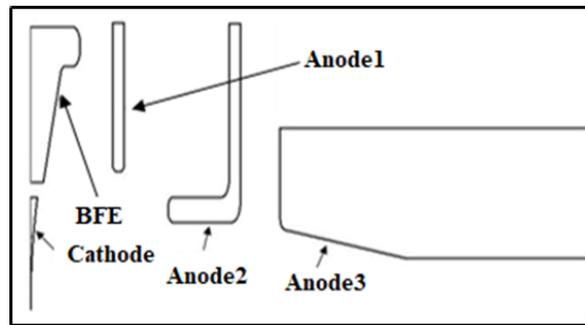


Figure 1. Synthesis model of Pierce type electron gun with different parameters for initial design.

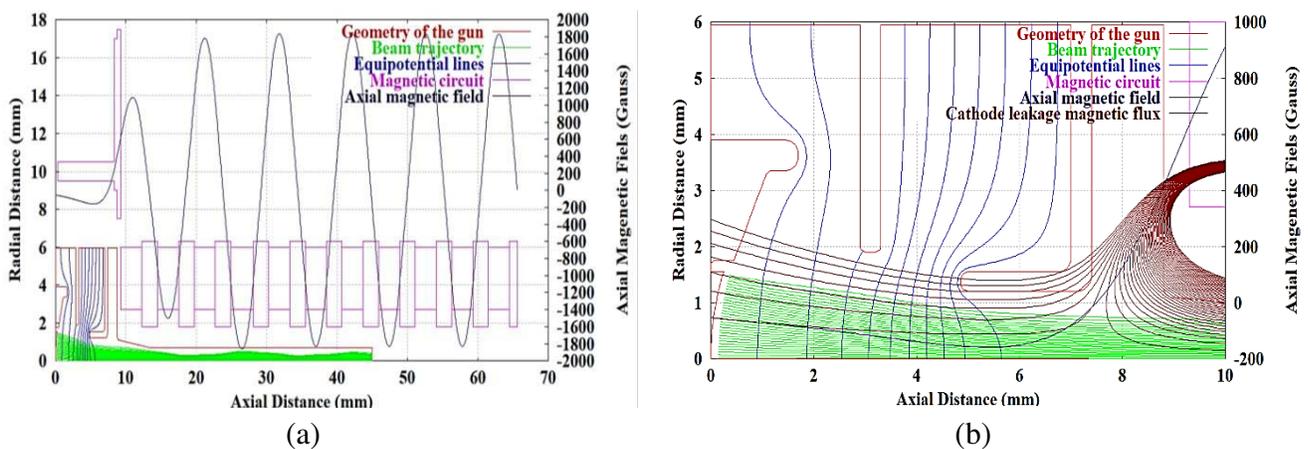


Figure 2. (a) Simulated beam optics under axially focused magnetic field, (b) zoomed view of equipotential line distribution and cathode leakage flux.

After achieving required beam optics, anode1 potential is varied to study its effect on beam current and optics. For confinement of the electron beam over the interaction structure, PPM (periodic permanent magnet) structure is optimized to get the axial magnetic field for minimum beam scalloping along the length of the TWT.

2.2. Results and Discussion

The flexi electron gun for X-band helix TWT has been modelled for required beam optics (Fig. 2). Fig. 2(a) shows the beam optics under focused PPM structure and zoomed view of equipotential lines distribution and cathode leakage flux in Fig. 2(b). Fig. 2 shows that a suitable beam optics is obtained with respect to geometry and position of the electrodes and their respective potentials shape equipotential lines from concave to convex in nature. Optimum geometry and potentials of the electrodes restrict beam optics to minimum beam scalloping, beam diameter and beam throw (minimum diameter position), etc. (Fig. 2). After achieving required beam optics, namely, beam current ~ 130 mA and beam diameter 0.6 (normalized with beam helix mean radius), rigorous study has been done to increase beam current by suitably adjusting electrode potentials without affecting beam optics, and it is found that anode1 plays a very important role in enhancing beam current without much affecting beam optics. With the increase in anode1, potential beam current increases linearly, and beam scalloping decreases (Fig. 3(a)). This improves beam optics, that is, with increased beam current, average beam diameter decreases nominally and may affect TWT efficiency by decreasing helix interception current. Also, with the increase in anode1 potential beam radius decreases, and beam waist/minimum position shifts (Fig. 3(b)). However, both decreases in beam diameter and shift of beam minimum are nominal,

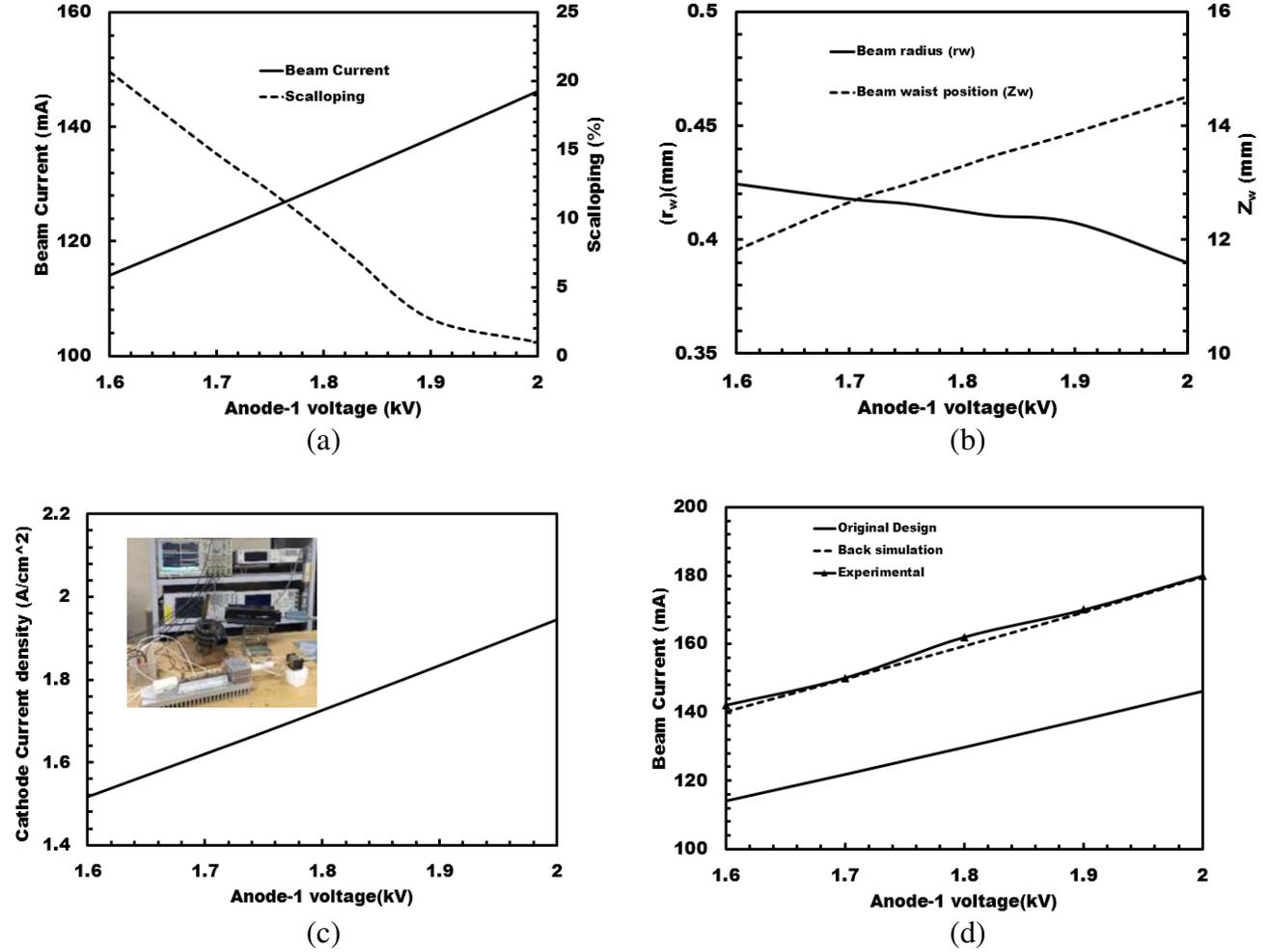


Figure 3. Effect of anode1 potential on electron beam optics: (a) beam current and scalping, (b) beam-waist (r_w) and beam-throw (z_w), (c) cathode current density and (d) beam current (original design (solid line), measured (line with symbol) and back simulation (dotted line)) (the inset picture in (c) shows the TWT in test bed).

which in turn reduces helix interception with the beam. However, the change in beam parameters with increased beam current is within accepted sensitive limit. Moreover, with the increase of anode1 voltage under the same EPC biased condition, cathode current density increases (Fig. 3(c)), as expected in the study. The increase in cathode current will improve TWT performance as the main parameter output power has direct relevance to beam current. Hence, such a flexible electron gun needs to be optimized with lower value of anode1 potential initially, and in subsequent time it can be increased to enhance beam current which decreases with time due to exhaustion of cathode. Thus, one may keep provision for anode1 voltage variation option during the development of electronic power conditioner (EPC).

Subsequently, engineering model of the gun is developed followed by design coordinates obtained from EGUN and integrated with the TWT (inset photo in Fig. 3(c) shows the TWT in testing bed), and it is observed that measured beam current is considerably high compared to designed value (Fig. 3(d)). To find the cause of discrepancy between design and experimental values, back simulation — validation of design based on experimental result is carried out with respect to geometry and potential of the electrodes. It has been observed that during engineering model, cathode has advanced by 0.1 mm from its original value with respect to BFE, which may be due to workmanship problem. Thus, effect of anode1 has a significant role in enhancing beam current with time due to exhaustion of cathode without much change in beam optics to avoid wear out failures in space.

3. CONCLUSIONS

Long life TWTs need to work over 15–20 years; however, performances degrade with time due to exhaustion of cathode. One may increase cathode power to pump more electrons which further aggravate cathode exhaustion and hence life. Thus, without increasing the filament power/cathode loading — floating on cathode high potential, one needs to have option for flexibility of electrode potential variation to increase beam current, and accordingly EPC may be designed. The shape, size, position, and potentials of individual electrodes play a vital role for desired beam optics. However, flexibility for variation of all electrode potential will arouse EPC design complexity. But from investigation, it has been observed that variation of anode1 in a multi-electrode flexi TWT plays an important role in enhancing the beam current, hence the life of the TWT. Also workmanship issues must be addressed seriously for the development of flexi electron gun.

Electron gun is the heart of TWT, and for suitable beam optics, it demands special design considerations if it is to be used for long life and reliable applications. Design through software packages and its transformation to engineering design also need equal importance. Any mismatch in electrical design and engineering design including fixture design in micron level changes TWT performance. Deviation of fixture design changes the position of the electrodes w.r.t cathode and deforms beam optics, which finally spoils the TWT. BFE plays a critical role in forming beam optics, and without disturbing BFE, an additional electrode, anode1 placed in between BFE and anode2, plays a critical role in enhancing the life of the TWT. Increase in anode1 voltage at a small step increases the total beam current, which decreases with time due to evaporation of Ba from cathode. Hence to increase beam current or to maintain constant beam current over long life, one needs to increase anode1 voltage at the steps as per requirement without major changing beam optics. However, the change in anode1 voltage at higher step will increase beam current drastically and deforms beam optics which in turn deteriorates TWT performance.

ACKNOWLEDGMENT

The authors are thankful to Director CSIR-CEERI for support and encouragement.

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