Vacuum 122 (2015) 103–116

Contents lists available at ScienceDirect

Vacuum

journal homepage: www.elsevier.com/locate/vacuum

Design of a sub-millimetric electron gun with analysis of thermomechanical effects on beam dynamics

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ARTICLE INFO

Article history:
Received 3 June 2015
Received in revised form
8 September 2015
Accepted 9 September 2015
Available online 11 September 2015

Keywords:
Charged particle beams
Thermoelectronic phenomena
Vacuum microelectronics
Computer modeling
Simulation

ABSTRACT

This paper describes a particular design of a thermionic electron gun employable in Sub-millimetric waves vacuum tubes and for spatial environment applications. Design strategies are proposed by providing closed formulas and dimensioning techniques. A multiphysics approach has been employed for studying the effect of multiple physics influencing factors due to the cathode heating over the beam dynamics. Operating temperature, thermal expansion displacements and external environment effects have been considered. This paper would give the academic knowledge for developing electron sources with narrow dimension providing an analytical approach followed by numerical modeling technique for virtual prototypes, which foresee the global behavior of this kind of devices while operating. For this aim, several strategies have been adopted and described in detail to obtain a simple model, which shows clearly these effects and their relations. The proposed modeling can allow for the correct operation in this range of narrow dimensions, where the operation is extremely critical while the cathode heating effects are present. According to this study, the appropriate materials and geometrical shapes for the beam-forming electrodes can be chosen.

1. Introduction

From all the way back of birth of the electronics, Electron Guns (e-Gun's) are the heart of electron devices. However, design techniques for such devices remained the same for many years. In this paper we propose a novel design approach suitable for sub-millimetric devices.

Vacuum tubes employ these electron source to produce the main electron current to be manipulated, in order to generate the output signals. In beam physics and radiation technology applications, e-Gun's are employed to produce a fundamental current of low energy electron. Such current can be injected in a linear accelerator to increase electron energy or can directly generate an ionizing radiation, by impacting on an opportune target [1–4].

In the microwave range and signal power levels over some Watts, the vacuum tube technology is mandatory and such amplifiers are typically based on travelling wave tube (TWT), in order to provide high power levels which solid-state technology cannot [5–7].

In the range of millimeter waves or sub-millimetric waves and signal power levels greater than kilowatt vacuum tubes as Gyrotrons or Free Electron Lasers have the dominance [8–11]. At the state of the art at the date of this paper, no solid-state amplifiers have been reported in literature with comparable power for similar applications. The Sub-millimetric range is a region of the electromagnetic spectrum that has remained until now mostly unexploited mainly due to the power limits of the available sources. In this context, vacuum tubes, such as for example Gyrotrons, represent the only way to obtain high power sources with compact dimensions.

One of the main difficulties in the realization of Sub-millimetric waves vacuum tube is the design and the realization of the electron gun. Due to the small dimensions, a Multiphysics approach is necessary in the electron gun design in order to study the effect of multiple physics influencing factors. Many aspects must be investigated at the same time such as mechanical stress or thermal expansion together with the behavior of charged particles immerged in electric fields.

The aim of this paper is to propose an analytical approach for dimensioning this kind of device and to provide the needed knowledge for developing numerical models of virtual prototypes, which foresee their global behavior while operating. To clearly

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http://dx.doi.org/10.1016/j.vacuum.2015.09.013
0042-207X/

show the deterministic consequences of thermo-mechanical effects over the beam dynamics, in this model, the complexity of particle release has been reduced to the least possible, for instance by simulating for the minimum reasonable number of particles. By adopting this approach, the alteration of the particle distribution can be evidently shown. The computational strategies and settings of the three physics computations involved in the model are described in the following discussion.

Traditional e-Gun's are typically based on thermionic emission and need to reach very high temperatures [12]. Cold field emission technology has been also developed; in this case, electron release is regulated by the material work function [13–14].

The main feature of a Sub-millimetric waves e-Gun is the small dimension (less than few millimeters) which makes it applicable to Sub-millimetric waves vacuum tubes [8–11] and also to particular experiments on electromagnetic radiations such as environmental studies [15] and electron microscopes for spatial applications [16–18]. In the latter case, a thermionic filament is desirable for several reasons. It requires a high vacuum of about 10^{-7} Torr; it is not very expensive and robust. However is not as bright as a cold field emitter and it generally has a typical source size from 30 to 100 μm versus 5 nm for a cold cathode [16–18].

Especially in thermionic devices, the power dissipation of the cathode produces a considerable temperature increase and induces a thermal expansion of both the cathode and the anode, which is warmed by the heat transfer operated by the non-ideal vacuum between anode and cathode regions.

In this range of small dimensions, an uncontrolled thermal expansion may produce destructive effects over the desired beam dynamics. Vacuum tube devices, using thermionic electron guns as beam sources, employee thermostatation systems placed on the vacuum tube surface, in order to control the temperature. These systems consist of liquid circuit passing into the tube metal volume connected to opportune liquid chiller to control the thermal expansion of the tube material without interfering to the cathode temperature of the connected e-Gun. The cathode temperature is controlled by heather voltage, while the rest of the e-Gun components are preferably cooled by natural air convection [5–12]. The e-Gun analyzed in this study is to be connected to a vacuum tube employing this strategy.

By a Thermo mechanical (TM) stationary analysis we can determine temperature and deformation [19] when the heat generated by the cathode has been diffused on all the reachable e-Gun components and the system has become thermally stable; due to the external temperature steady over all the e-Gun outer surfaces, which are exposed to the external environment.

Since the Electrostatic (ES) fields are altered by the particles presence, we have a two-way coupling between the particles and field: the field exerts a force on the particles and the particles exert a space charge on the field. Moreover, the variables of the problem are also dependent on the Coulomb forces interactions between the particles. For these reasons, is necessary to solve the problem for the particles and fields simultaneously by coupling a Charge Particle Tracing (CPT) and an ES analysis [19]. Ray tracing and Particle in Cell codes using an iterative scheme are capable to find the correct characterization of the e-Gun particle trajectories representation with a description of energy and velocity inside the acceleration–focalization chamber. However, a time dependent analysis has been chosen to solve for this kind of problem.

The cathode electron density and the charge distribution of the electron clouds in the accelerating axis of the e-Gun can be estimated and the electron spot disposition in several transversal cross sections of the device can be evaluated at different instants. In thermo-mechanical operation, the emitting surface of the cathode, together with the beam-forming electrodes, tends to move from the original disposition to a temperature steady state position. In this condition the desired beam distribution changes and the desired behavior of the beam spot is disposed in a different position. Such thermally induced alterations of the beam dynamics decrease the e-gun performances with respect to the design specifications. For vacuum electron devices, only with opportune Multiphysics modeling based design is possible to obtain a correct operation when the device is subjected to the thermal stresses and temperature alterations.

The proposed e-Gun is designed in order to be installed in micro vacuum tubes [8–11] and, since it has dimensions of about few millimeters; the cathode heating has a critical effect over the whole structure. In order to control the thermal expansion, without interfere with the cathode operation; we propose to incorporate the anode in a controlled heat sinking system. This system can be implemented through a high thermal conductivity material slab connected to a heat exchanger employing a liquid chiller or forced air cooler. This study considers an e-Gun surrounded in a simply air filled space but, in the future, active heat sinking systems could be employed in order to improve cooling, reduce warm up time and stabilize possible temperature transients.

2. Materials and methods

An e-Gun suitable for Sub-millimetric waves application has been designed by following the theory of electron beam design reported in Ref. [15]. The beam dimensions are consistent with vacuum devices already studied in the THz frequency range [20–23]. In particular, the current and voltage levels are chosen to produce an electron beam which, when impacts on an opportune target, can produce a kind of radiations suitable for space flight application studies and atmospheric spectrometers [15–18]. We clarify that the proposed e-Gun is not designed for Gyrotrons, since such devices need a hollow electron beam and therefore a ring-shaped emitter but it can be employed as a source for micro vacuum tubes [20–25].

The e-Gun studied in this paper would be employable to simulate space environments for accurate testing of materials and systems as for the low energy electron gun “Skevington 3000” developed at NASA Marshall Space Flight Center. Such device uses a 0.1 mm tungsten cathode which is wound into a filament heated through Joule heating and can provide an electron beam of 2.3 mA with energy of 1 keV [26].

The proposed e-Gun would increase the energy of device described in Ref. [26] to 3 keV while lowering the current to 1.6 mA in order to be implemented as a micro vacuum device. For this aim, the e-Gun electromagnetic design has been performed by following the technique proposed in this paper which is based on several strategies, mainly derived by Refs. [12,27], to obtain a miniature e-Gun of Sub-millimetric dimensions, having a particular attention to obtain a maximum size containable in a cube of 5 mm side. The proposed e-Gun comprise of a flat emitter sitting between Pierce electrodes. This strategy allows for a compact device with potentially good focusing performances without the use of confining magnetic fields. In order to respect the maximum external size, the maximum length of the interaction region comprised between anode and cathode should be contained in 1 mm, expecting a maximum focal length less than 2 mm.

At these narrow sizes, the Pierce Gun would be difficult to produce and particular attention to the production process is needed while a multiphysics approach allows for estimating possible troubles which could affect the fabrication processes. Recent advances in micro fabrication technologies have hallowed for the implementation of emitter cathodes on a micron scale, using the Photolithography. This technique is employed for miniature