Sub-Millimetric Vacuum Electron Gun Design and Characterization

A. Leggieri*[1], G. Ulisse[1], F. Di Paolo[1], F. Brunetti[1] and A. Di Carlo[1]
[1]Department of Electronic Engineering, University of Rome "Tor Vergata", Italy
*A. Leggieri: Department of Electronic Engineering, University of Rome "Tor Vergata",
Via del Politecnico, 1, 00133, Rome, Italy, alberto.leggieri@uniroma2.it, leggieri@ing.uniroma2.it

Abstract: This paper presents the design of an electron gun that could be employed for vacuum tubes operating in the THz range. In this context, vacuum tubes, such as traveling wave tubes (TWT) or klystrons, represents the only way to obtain high power sources with compact dimensions.

One of the main difficulties in the realization of THz vacuum tube is the design and the realization of the electron gun. Since the dimensions are quite small (few millimeters) a Multiphysics (MP) approach is necessary in the electron gun design in order to study the effect of the multiple influencing factors.

In order to start the developing of MP models for these devices, a Particle Tracing (PT) simulation, based on a COMSOL Multiphysics, for a vacuum Electron Gun (E-Gun) has been performed. PT simulation in a MP ambient can be extended to a thermal and structural mechanics simulation.

Keywords: Particle Tracing, THz, Vacuum Tubes, Electrostatics, Charged Particle Tracing.

1. Introduction

ELECTRON GUNS are fundamental parts of the Vacuum Tube (VT) devices. In this structure, the charges emitted by a cathode (provided by a current source) are focalized and accelerated by an opportune Electrostatic (ES) Field (provided by a voltage source).

Since the dimensions of THz vacuum tubes are quite small (few millimeters) a Multiphysics (MP) approach is necessary in the electron gun design in order to study the effect of the multiple influencing factors. Many aspects can be investigated at the same time such as mechanical stress or thermal expansion together with the behavior of charged particle in electrostatic and magnetostatic fields.

In order to start the developing of MP models for these devices, a Particle Tracing (PT) simulation, based on a COMSOL Multiphysics, for a vacuum Electron Gun (E-Gun) has been performed. The current level and beam dimensions, chosen for the electron gun design, are consistent with vacuum devices already studied in the THz frequency range [1-4].

Since the ES field is 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 couple a PT and an Electrostatic (ES) analysis [5].

These coupling effects inside the acceleration-focalization chamber require a time dependent (TD) analysis, in order to perform a PT characterization of the E-Gun particle trajectories representation with a description of energy and velocity. It allows besides to estimate the cathode electron density and the charge distribution of the electron spot in several transversal cross sections of the E-gun.

A Finite Element Method (FEM) based Multiphysics simulation using COMSOL can couple PT and ES analysis by calculating and storing ES Voltage and PT trajectories information. In order to decrease computational time and resources maintaining accuracy, the device model is organized by using several strategies allowed by COMSOL.

Moreover, by using a Multiphysics computation code, other physics can be added and different effects can be estimated.

The 3D geometry of the electron gun is reported in Figure 1. In the model, a drift tube has been added to the geometry, in order to evaluate the beam properties, it is indicated in Figure 2.

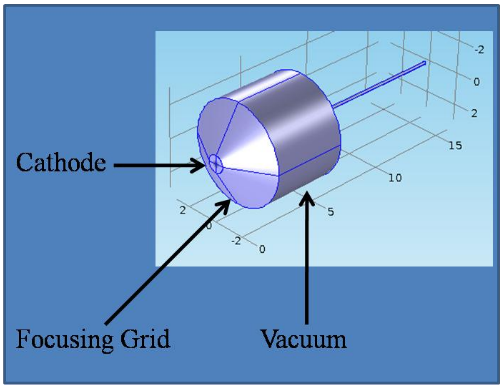

Figure 1. E-Gun Geometry: Cathode and focusing grid are assigned to PEC material separated by vacuum as dielectric.

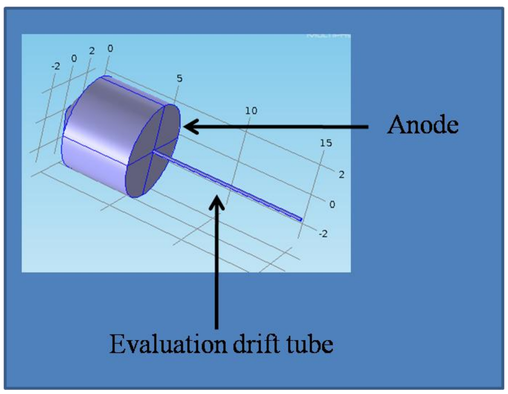

Figure 2. E-Gun Geometry: Anode and evaluation drift tube are assigned to PEC material.

2. Use of COMSOL Multiphysics

The model is organized by using Charged Particle Tracing (CPT) and Electrostatics (ES) COMSOL modules. The used materials are Perfect Electric Conductor (PEC) for the electrode surfaces and Vacuum for the volume of the e-Gun.

2.1 Electrostatic Module

The ES module is employed to describe the Electrostatic field formulation of the problem by using the main following ES module features:

- Charge Conservation: This feature describes the macroscopic properties of the medium (relating the electric displacement D with the electric field E) and the applicable material properties [6].
- Electric Potential: This feature is used to set the anode electric potential to 10[KV] and cathode electric potential to zero.

2.2 Charged Particle Tracing Module

The CPT module is employed to give the rules on how calculate the particle trajectories in function of the prescribed particle characteristics and Electric Force (EF) resulting by the Electric Field computed by the ES analysis. In order to perform the CPT analysis in these conditions, the CPT module uses the main following features:

- Particle properties: this feature is employed to describe the electrons, by its mass and charge.
- Inlet: In order to simplify the particle emission, by neglecting the statistical behavior, the electrons are released from the cathode boundary only on its normal direction (y) with an initial velocity determined by:

$$V_y = \sqrt{\frac{2U_0}{m_0}}$$

Where U_0 is the design initial potential energy of the electrons and m0 the electron mass.
The value of U_0 is set to 5 [eV], resulting in v_y = 1.33·106[ms^{-1}].
Since the cathode current density is constant in time and on the cathode surface, the charge release is represented by a short pulse sequence with initial null value, so that the number of particle per release is:

$$N = \frac{Js\Delta t}{e}$$

Where J and s are respectively the cathode current density and surface, e the elementary charge of the electron and Δt is the time interval between two consecutive charge releases. By setting $J = 2$[A·cm^{-2}], s = 7.85·10^{-7}[m^2] and Δt = 4.36·10^{-11}[s], we have N=4.27·10^6 particles per release.
In order to save computational costs, this

number has been decreased and, as explained below, a charge multiplier factor has been introduced, in order to respect the space charge effect.

- Particle field interaction: This node adds two-way coupling between the particles and field. In order to model at the same time the space charge effect (exerted by the electrons on the ES field) and the force (exerted by the electric field on the charges) this node has been added in the CPT COMSOL module. Since the number of charges per release has been set to N^1=427, a charge multiplier factor $n = 10^4$ has been specified in this feature. The charge multiplication factor can be calculated by $n=N/N^1$, as synthesized in Figure 3.

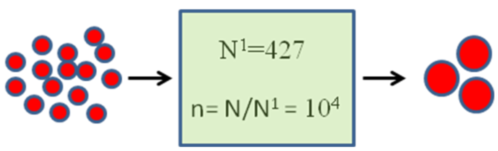

Figure 3. The charge multiplication factor employed to reduce computational cost.

- Electric Force: This feature is employed to define the electric part of the Lorentz force. The particles are accelerated in the same orientation as the electric field.
  The force is specified via the electric potential computed time dependently by the ES module, by setting “V = mod1.V” [5].

- Particle-Particle Interaction: This feature is employed to include the Coulomb interaction force between charged particles to the total force. The particle position is step by step updated, and the process repeats until the specified end time for the simulation is reached [5].
  The resulting electric field is altered by the presence of the particle-particle interaction, which, by the particle-field interaction, affects the total electric force. This principle is schematized in Figure 4.

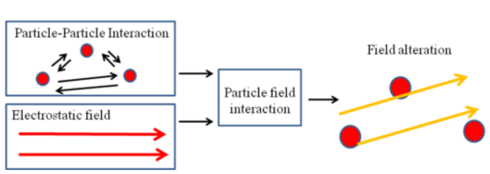

Figure 4. The resulting electric field is altered by the presence of the particle-particle interaction.

2.3 Time dependent solver

The time dependent analysis has been set to start at time t=0 and end at $t=10 \cdot \Delta t$, by steps of Δt, performing the analysis in 10 steps. In order to see the initial current transient, the particle release has been set to start at $t=\Delta t$ and end at $t=10 \cdot \Delta t$, by steps of Δt.

3. Results

By solving a time dependent analysis on the described device, the following results are been obtained:

3.1 Particle Energy and Velocity

- Particle Energy: Maximum energy reached by the particle is W = 10.41 [KeV], as shown in Figure 5.

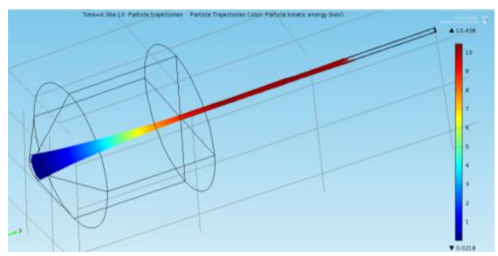

Figure 5. Particle Energy.

- Particle velocity: Maximum speed reached by the particle is $v = 6.06 \cdot 10^7$ [ms^{-1}], as shown in Figure 6.

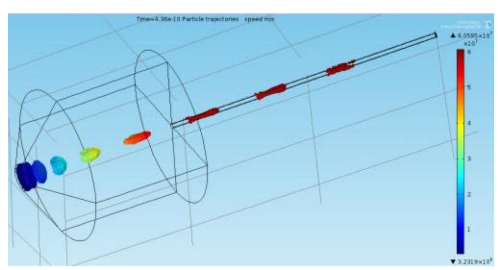

Figure 6. Particle velocity and focusing effect.

3.2 Beam spatial distribution

- Beam Waist: the beam waist is located close to the anode interface at a distance from the cathode d = 6.0 [mm] and it has a radius r = 0.1 [mm], as shown in Figure 7.

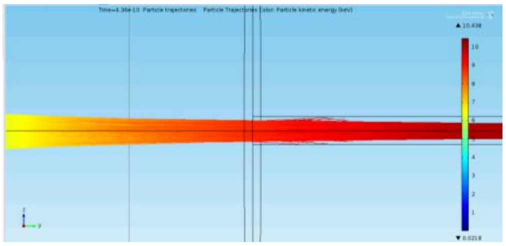

Figure 7. Beam Waist.

- Particle cross sectional distribution: The particle spot has been described by using the Poincare Map, as shown in Figure 8.
  Since the cathode radius is 1[mm], the area compression factor of the beam spot is $\alpha = 100$.

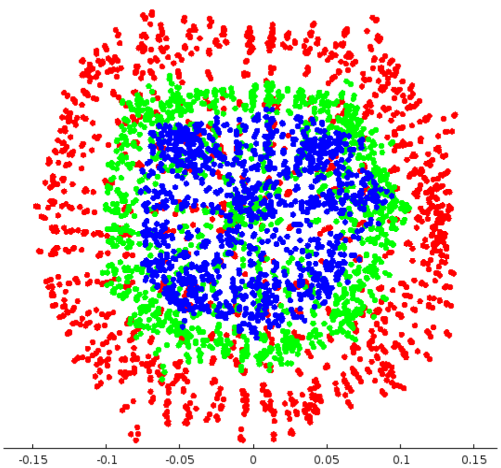

Figure 8. Spot cross sectional distribution: Y=3.8 mm red; Y=4.8 mm green; Y=6.0mm blue (anode).

3.3 Cathode current density

We have checked the self consistency of the proposed model by observing the cathode current density which, terminated the initial transient, is stable around the design value $J = 2[\text{A}\cdot\text{cm}^{-2}]$, as shown in Figure 9.

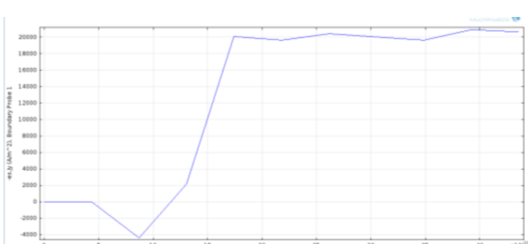

Figure 9. Current Density.

4. Conclusions

We have seen that one of the main difficulties in the realization of THz vacuum tube is the design and the realization of the electron gun. Since the dimensions are quite small (less than few millimeters) a Multiphysics approach is necessary in the electron gun design in order to study the effect of the multiple influencing factors (thermal expansions and mechanical stresses).

An electron Gun for THz application has been designed, consistently with vacuum devices already studied in the THz frequency range. In order to start the developing of MP models for these devices, a Particle Tracing (PT) model for a vacuum Electron Gun on COMSOL Multiphysics (Finite Element Method based), has been developed. A fully coupled time dependent analysis of Charged particle tracing with electrostatic field has been performed and expected results have been obtained. Without any magnetic field we have obtained a beam area compression factor of 100.

8. References

1. A. Di Carlo et al, “The European project OPTHER for the development of a THz tube amplifier,” *International Vacuum Electronics Conference*, pp. 100 - 101, 2009.

2. Kenneth B. K. Teo et al, “Microwave devices: Carbon nanotubes as cold cathodes,” *Nature*, 437, 2005.

3. J. Tucek, D. Gallagher, K. Kreischer, R. Mihailovich, “A compact, high power, 0.65 THz source,” *International Vacuum Electronics Conference*, pp. 16 - 17, 2008.

4. G. Ulisse, F. Brunetti, A. Di Carlo, "Study of the influence of transverse velocity on the design of cold cathode based electron guns for THz devices" *IEEE Transactions on Electron Devices*, Vol. 58, Iss. 9, pp. 3200-3204, 2011.

5. *COMSOL Particle Tracing Module Users Guide, Version* May 2012, COMSOL 4.3.

6. *COMSOL AC/DC Module Users Guide* Version May 2012, COMSOL 4.3.