Abstract—A computational model of a Buncher cavity for millimetric klystron following a Multiphysics approach is proposed in this paper. At these narrow dimensions, the device is critically exposed to multiple physics effects, due to the power dissipations and external environment, influencing the electromagnetic performances. The cavity is integrated with a carbon nanotube cold cathode in order to reduce the resonance frequency shift. Electromagnetic fields and scattering parameters have been tested in operative conditions by concurrent computation of coupled thermodynamic, fluid dynamic, structural mechanics and electromagnetic simulations. This approach has suggested the appropriate materials and geometrical shapes.

Keywords—Klystron, microwave devices, multiphysics simulation, numerical modeling, vacuum tubes.

I. INTRODUCTION

Millimeter wave applications for high power, around the Kilowatt, employees vacuum tube technology. Klystron and TWT are the most diffused devices for broad band applications [1]. Klystrons are well known vacuum tube amplifier employing a set of resonant cavities as grids and may be developed through several interesting solutions [2-3] and can operate around 100 GHz, [4-6].

In millimeter and sub-millimeter wave frequency bands, solid-state devices present lack of performances, overcome by vacuum tubes, especially by Klystrons employing cold cathodes [7]. In a Klystron, the electron beam produced by an electrostatic gun, first interacts with the Buncher cavity, where undergoes the force a low energy alternate field that modulates the electron velocity. As the beam has crossed an opportune distance from the Buncher, the velocity modulation become a modulation of the charge density and the beam, forwarded in another cavity, induces an oscillating field stronger than the first. Finally, the beam is collected at the anode. These dynamic results in an amplification of the signal. Since no magnetic field is required, klystrons are good candidates for micro vacuum tube realization [7]. Recent advances in micro fabrication have hallowed for the implementation of emitter cathodes on a micron scale, using the Photolithography for miniature vacuum tubes [7]. Micro-electro-mechanical systems (MEMS) technology overcomes the limits of traditional micro fabrication. The proposed device can be built by such techniques over a silicon wafer [8]. Particular Klystron design techniques have been recently developed for the photolithographic fabrication [5-6]. In millimetric waves, very small beam dimension are required [9] and cold cathode technology can be useful.

This study proposes the analysis of the Buncher cavity of the klystron while it experience the heating effects of its power dissipations, due to the wall current, and the electron gun closely connected. The analysis follows a Multiphysics modeling approach, in order to prevent alterations of the electromagnetic (EM) behavior, while exposing the device to these multiple physics factors. In order to control the temperature and thermal expansion, an opportune airflow is used. It has been has been introduced for cooling the external walls by following the strategy described below. The Buncher has the shape of a reentrant cavity: Typically, if the cavity radius is increased, the resonance frequency decreases and, albeit often with less effect, if the cavity gap increases the frequency increase. An isotropic thermal expansion may dilate the cavity Buncher mainly decreasing the operative frequency. This effect can be compensated by decreasing the surrounding temperature, requiring important cooling systems. In the proposed application, mechanical constraints and possible direction of thermal expansions have been considered, in order to obtain the desired compensation of the frequency lowering. For this reason, the airflow has been prescribed oriented for cooling off the lateral surfaces more than base surfaces. This strategy allows for decreasing radius dilation with respect to the cavity gap dilation.

The geometry and materials of the main model are reported in Fig. 1. The solid material is a block of Silicon at which interior, the vacuum region of electron gun and Buncher is present. A layer of Silver is disposed on the internal surfaces except for the circular lateral surface of the gun that insulate the anode to cathode. Many aspects have been investigated at the same time, such as mechanical stress or thermal expansion, together with the electromagnetic behavior of the device through a Finite Element Method Multiphysics computation. In the computational model, the geometry in Fig. 1 has been inserted inside a box containing airflow with other environmental conditions as temperatures and mechanical constraints. By a Thermo-mechanical (TM) analysis, temperature and deformation have been determined considering the heating effects due to the resonator power dissipation superposed to that of the cathode, when whose heat flux has been diffused on all the reachable components, cooled externally by an opportune airflow.
For this aim, a Thermodynamic (TD) and Fluid Dynamic (FD) analysis have been coupled and the resulting temperature distribution and matrices of displacements is obtained. These displacements have been employed to obtain a deformed geometry by Moving Mesh (MM) dedicated interface and storing temperature information [10]. Electromagnetic analysis has been executed on the new meshes receiving the temperatures evaluated by the TD and FD studies. A first EM analysis has been employed to calculate the microwave power dissipations when wall current flows on the cavity walls while it receives the operative input signal (1 W mean power) at the input port. This power dissipation has been prescribed into the thermodynamic calculation as a heat power source. A schematic diagram of the multiphysics architecture is reported in Fig.2.

II. ELECTROMAGNETIC ANALYSIS

The Klystron Buncher is a cylindrical resonant cavity, operating in a quasi TM
tm 010 mode, at these frequencies it has a radius around one millimeter. A waveguide aperture is used for the cavity coupling with the input signal. A doubly tapered section of two wavelengths is terminating into the cavity with a short side tapering superposed with a double 45° shaped tapering of the long side. A tapering of the long side may lead the propagating mode under cutoff. A WR-8 waveguide flange is available at the input port for the connection of standard alimentation device. A reentrant squared cross section cavity has been designed by applying several design proportions. The analytical design of the cavity has been performed solving the system of equation described by Carter [11]. By referring to this nomenclature, cavity dimensions have been set to r1 = 0.16 mm, r2 = 0.22 mm, r3 = 0.8 mm, z1 = 0.5 mm, z2 = 0.16 mm, z3 = 0.25 mm. The unperturbed analytical frequency of resonance is 132.32 GHz. Particular cavity design techniques, based on higher order mode, allow for a further reduction of the dimensions extending the applicability to the THz range [5-6].

A computational electromagnetic analysis has been performed by the RF module of Comsol Multiphysics to solve the wave equation in the frequency domain (1) [10].

$$\nabla \times \mu_r^{-1} (\nabla \times \mathbf{E}) - k_0^2 (\varepsilon_r - \frac{j \sigma}{\omega \varepsilon_0}) \mathbf{E} = 0 \tag{1}$$

The maximum return loss at the resonant frequency of 131.68 GHz is 21.0 dB. The resonance tends to the critical coupling. The prescribed design average power input for the proposed device is 1 W, corresponding to an entering power in the cavity of P = 0.992W resonating in the cavity. While receiving this power, at the resonance, the axial electric field distribution along the gap path have a maximum of 1.5MVm

The electron source employed in this study is a carbon nanotube (CNT) emitter array. The e-Gun has been designed by following the theory of electron beam design reported in [12]. The beam dimensions are consistent with vacuum devices already studied in millimeter and sub-millimeter frequency range [9]. The e-Gun is designed to produce a 16 mA beam of 10 keV electrons at the Buncher interface.
III. THERMODYNAMICS AND FLUID DYNAMICS ANALYSIS

The power dissipation of the cathode produces a temperature increase and induces thermal expansion. In this range of small dimensions, an uncontrolled expansion may produce destructive effects over the desired behavior. A Finite Element Method simulation, using COMSOL Multiphysics, have been employed for the TM computation. The first step was the coupling and solving of TD and FD analysis [13]. These studies have been performed at the thermal steady state when the cathode temperature and cavity dissipations are fixed at operative values and the structure is subjected to an air flow of 2 ms⁻¹ velocity oriented towards the lateral surface, opposite to the side of the input flange. In this condition the thermal equilibrium is reached since all transient events are terminated. Heat Transfer has been computed by solving the Heat Equation in the steady state condition (2) [10].

\[ \rho C_p u \cdot \nabla T = \nabla \cdot (k \nabla T) + Q \]  

where \( \rho \) is the material density (kg·m⁻³), \( C_p \) the heat capacity at constant pressure (J·kg⁻¹·K⁻¹), \( u \) is the velocity field (m·s⁻¹), \( k \) the thermal conductivity (W·m⁻¹·K⁻¹) and \( Q \) is the heat power density (W·m⁻³). The power dissipation calculated in a preliminary Electromagnetic analysis has been prescribed on the Buncher walls as surface density power source, introducing an equation similar to (11) where the \( \nabla \) operator is simply a normal unitary vector and \( k \) has the negative sign ahead. The cathode surface has been considered at its nominal operative temperature that is 35°C.

The air motion is modeled with a single phase laminar flow and computed by solving the system of (3) and (4) in a stationary analysis [13].

\[ \rho(u \cdot \nabla)u = \nabla \left[ -pI + \mu (\nabla u + (\nabla u)^T) \right] - \frac{2}{3} \mu |\nabla \cdot u| + F_y \]  

(3)

\[ \nabla \cdot (\rho u) = 0 \]  

(4)

where \( p \) is the pressure, \( \mu \) the dynamic viscosity (Pa·s) of the material (the air) and \( F_y \) is the force per unit volume (N·m⁻³). The symbol \( I \) stand for the identity matrix and \( T \) for the transposing operation. The external environment temperature is \( T_{ext} = 25°C \), consistently with a typical environment temperature condition.

While the airflow enters the box, it is at this temperature, and then by exchanging heat with the device external surface, it becomes warmer approaching to a maximum temperature of 34.9°C, when it hits the device. This effect and the cooling of lateral surfaces can be noted in Fig. 3. This is the needed effect that allows to contain the dilation of the cavity radius. As shown in Fig. 4, the maximum temperature reached internally is 35°C. This is due to the cathode operative temperature at the lower surface.

IV. STRUCTURAL MECHANICS ANALYSIS

This analysis is the last step of the TM computation. It receives the output temperature form the previous computation and calculates the thermal expansion of the material, obtaining the spatial displacements and stresses. Since temperatures are dependent to the displacements, this analysis has solved the system of stress steady state equation (5) fully coupled with the computation of the (2), (3) and (4) [10].

\[ -\nabla \cdot \sigma = F_y \]  

(5)

where \( \sigma \) is the stress (Nm⁻²). The mechanical boundary conditions have been chosen in order to leave device external walls free from any constriction, ensuring the ability to swell. Only one face is fixed that is the face where the cathode is mounted because is used for supporting the device by a connection to the cathode assembly. The solid model is intended as isotropic and the structural transient behavior as quasi-static. In order to underline the deformation, stress and displacement are been plotted with a magnified scale, so that the deformation scale has been increased. In the following figures, black outlines represent the original conformation, and the stained volume represents the deformed structure.

The computed global temperature distribution over the whole device walls has induced a maximum stress of about 27.5 MNm⁻² (Fig.5) located at the edges of the warmest face which is fixed to the rigid support. This is due to the high stiffness of silicon that counteracts the binding forces at the fixed surface. The internal shape, more free to deform, is less stressed than this interface, farther from which, the maximum total displacement is and is about 362 nm (Fig. 6). This is due to the low thermal expansion of silicon and to the fact that this face is at 25°C, only 5°C more than the reference temperature (20°C). It can be also noted the achievement of the desired displacement: More displacement is directed along the axial direction \( z \) (the direction of the cavity gap) and less along the radial direction \( x \).
V. ELECTROMAGNETIC BEHAVIOR IN OPERATIVE CONDITION

The EM analysis is coupled to the previous calculation by MM dedicated interface and storing temperature information [10]. The MM computation moved the mesh in function of the displacement computed by the SM analysis. Subsequently, EM analysis has been executed on the new meshes receiving the temperatures evaluated by the TD and FD studies. In Fig. 7 we can observe the streamline distribution of the electrodynamics fields for the bunching along the central plane. In cold and in thermo mechanical operating conditions respectively $E_{\text{ACmax}} = 2.39$ and $E_{\text{ACmax}} = 2.99$ MVm$^{-1}$ are reached. It can be noted that these fields are distribute in the pattern of the desired resonant mode, the quasi TM$_{010}$ expected by [11]. The scattering parameters in cold and in TM operating conditions have been documented and reported in Fig. 8. In this analysis has been also considered the case of thermal insulation of the device. In this situation the device reaches a thermal steady state at the cathode temperature of 35°C, causing an isotropic thermal expansion that produces a considerable frequency lowering. This effect may happen if the system were enclosed in an insulated box, a situation preferably to be avoided but note.
The dilation of the Buncher radius produces a dilation of the resonance wavelength, hence a frequency decreasing occurs. As shown in the red curve of Fig. 13, the resonance frequency of the Buncher from the cold condition (where it has the value of $f_1 = 131.68$ GHz) decreases to $f_2 = 131.17$ GHz if only the thermal heating is present without cooling air flux. In this condition a difference of 510 MHz can be noted between the two frequencies. While the cooling air flux is operating, the controlled temperature at the Buncher lateral surfaces contains its shape alteration. Anyhow, the base surface, where the beam output hole is located, tends to expand straightly, since is less refrigerated, due to the positioning of the air flux streamlines which are crossed to longitudinal axis of the Buncher. This effect allows for a frequency increase, as shown in the green curve of Fig. 13 because the cavity gap is dilated. In this condition, the resonance frequency moves to $f_3 = 131.87$. The return loss decrease from 18.7 to 18.4 dB. This is a very small disadvantage if is compared to the advantage obtained over the frequency shift, which is decreased to 190 MHz, as discussed in the following text while treating the bunching field amplitude variation. It’s evident as an opportune exterior shape can re-increase the performance of the device while it undergoes the operative influencing factors.

The longitudinal distribution of the electrodynamics bunching fields in cold and in thermo mechanical operating conditions is reported in Fig. 9. In this analysis, in addition to the case of considering the sole cathode temperature without airflow, another effect has been highlighted: If the resonance frequency changes, is opportune to change the resonance frequency of the load (typically a resonant device) connected to the Klystron in order to transfer the maximum power also in operative conditions. If the load operates at $f_1$ while the Klystron is operating to $f_2$ or $f_3$ due to the TM alterations, to the load a poor power can be transferred, since the bunching field at the cold frequency is reduced to less than an half (see cyan curve in Fig. 9). If the load is tuned to follow the operative frequency of the Klystron, the transferred power remains the same even if the frequency is shifted.

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**Fig. 7.** Electrodynamic field distribution (MV/m): Cold (left) and working conditions (right).

**Fig. 8.** Scattering reflection parameter $S_{11}$ in dB: Cold and working conditions.

**Fig. 9.** Axial electrodynamic field distribution (MV/m): Cold and working conditions considering cathode heating and air cooling.
VI. CONCLUSION

The Multiphysics design of a 130 GHz klystron Buncher is described in this paper. The proposed device can be micro-fabricated by micromachining techniques over a silicon wafer. In this frequency range, very small beam dimension are required, representing a critical aspect since the multiple physics influencing factors (due to the heating effects and power dissipations) can modify the electromagnetic behavior of the device. In order to reduce thermal expansion of the material typical of the classical thermionic cathodes, a Carbon nanotube cold cathode is employed. Even though the cold cathode operates at a temperature of 35°C it produces considerable effects at the design frequency. The proximity of the Buncher cavity to the electron gun represents a critical aspect: The Thermo-mechanical modification affects the bunching electric field, modifying the desired device behavior.

A multiphysics design approach using COMSOL has been employed to ensure the future correct operation. By a Thermo mechanical analysis, coupling Heat Transfer and Structural Mechanics module, temperature and deformations have been determined when the heat generated by the cathode power dissipation has been diffused to the system, cooled by an opportune airflow. This study gives the requirements for a cooling fan. Thermo-mechanical displacements have been computed and the Moving Mesh (MM) dedicated interface has been used to obtain the deformed geometry where electromagnetic analysis is performed. Scattering parameters at the input port and axial electric field of the Buncher cavity have been calculated. The Thermo-mechanical alteration of the e-Gun shape and electromagnetic losses does not modify significantly the desired electrostatic fields but significantly acts on the resonator, due to the very narrow dimensions.

As demonstrated from this modeling, the silicon background material present very low thermal expansion coefficient which is not significantly subjected to deformations when a cold cathode is employed. This is an advantage of using cold cathode and cooling airflow, which inhibits destructive thermal effects. Furthermore, has been shown a strategy to allow for a frequency shift compensation through the control an anisotropic thermal expansion, placing airflow in an opportune direction to cool some surface instead of others. Several strategies have been adopted to obtain a simple but reliable model and the proposed approach has allowed to select the appropriate materials and shapes.

REFERENCES