Multiphysics Design of a 130 GHz Klystron

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Outline

- Introduction
- Operative principles
- Motivations
- Klystron Features
- Numerical model
- Simulation Results
- Conclusions

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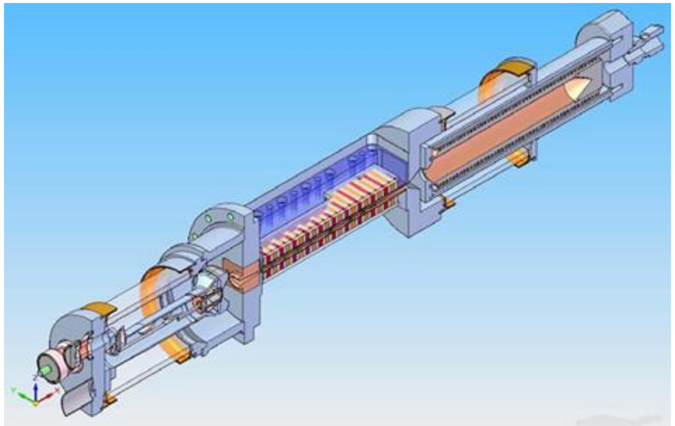
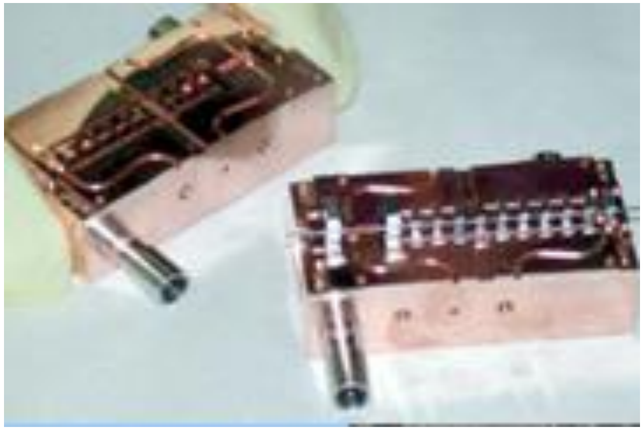
Introduction

3 GHz Klystron

91 GHz Klystron



Microfabrication

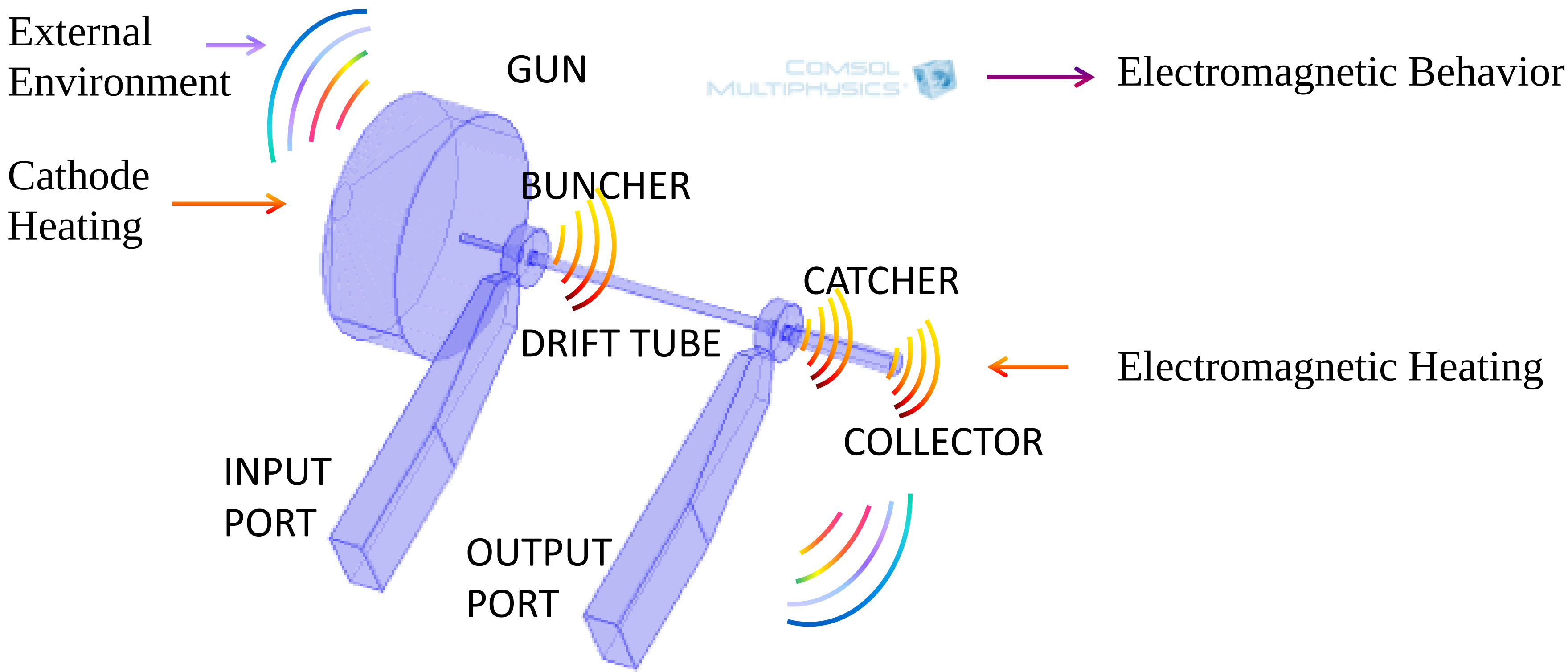


Millimetric wave applications for high power, around the Kilowatt, employees vacuum tube technology. Klystron and TWT are the most diffused devices for broad band applications. Klystrons are well known vacuum tube amplifier employing a set of resonant cavities as grids and may be developed through several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

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.

Introduction

Multiphysics-based model Design



The Multiphysics analysis of a **130 GHz klystron** is described in this paper. Critical quantities are exposed to multiple physics effects acting on narrow dimensions modified by power dissipations. The proposed device uses an integrated injection/bunching section described in last COMSOL conference appointment. The system is based on **carbon nanotube cold cathode** and opportune **airflow** to control the temperature. The multiphysics design is performed on COMSOL in order to ensure the desired behavior in operative conditions.

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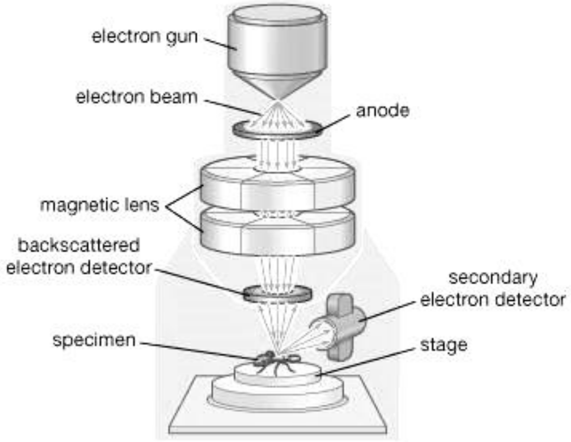
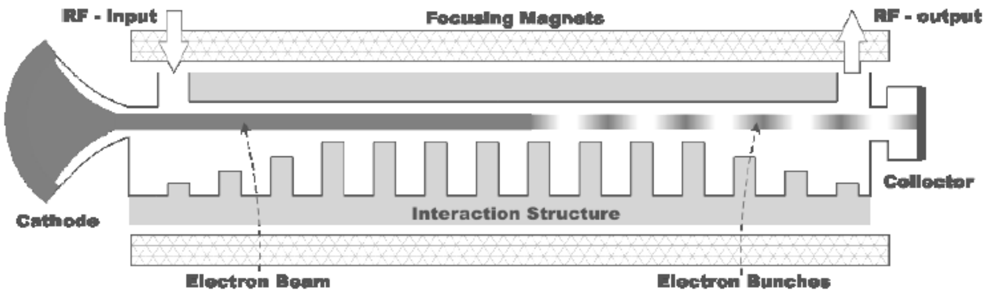
Introduction

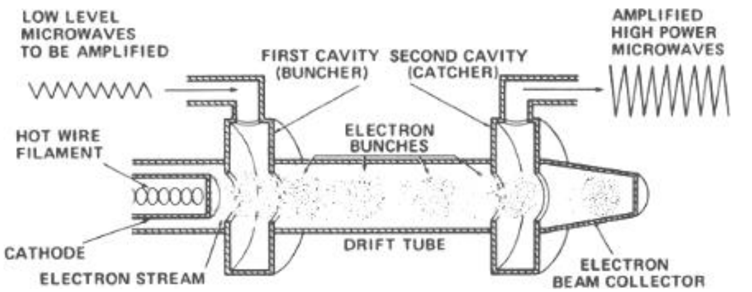
ELECTRON MICROSCOPE



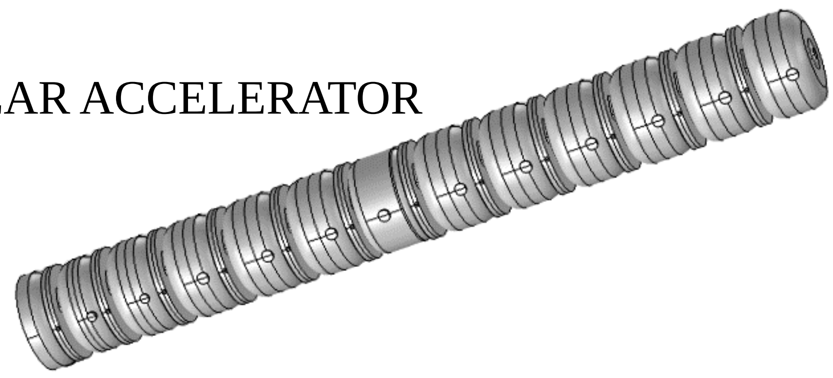
TWT



KLYSTRON



LINEAR ACCELERATOR



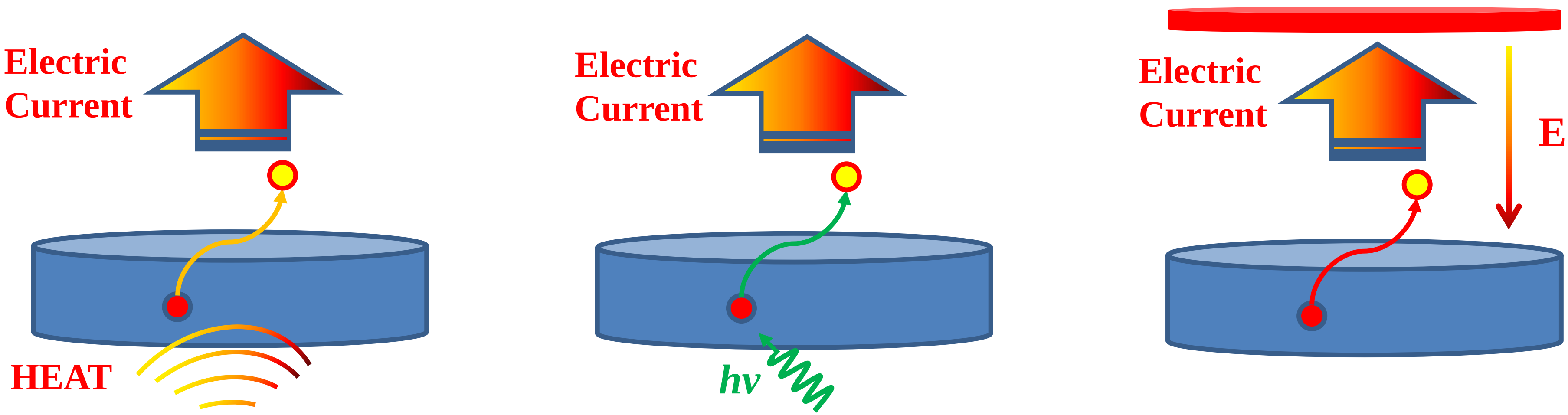
In many applications **very small beam dimension** are required as sub-millimeter waves vacuum tubes, electromagnetic environmental instrumentation and electron microscopes for spatial applications.

Vacuum tubes employ **electron gun's** as sources for the main electron current to be manipulated in the tube.

Operative principles

Cathode Electron Emission

Thermionic emission | Photo-electric emission | Field emission



Electron emission can occur under three fundamental processes:

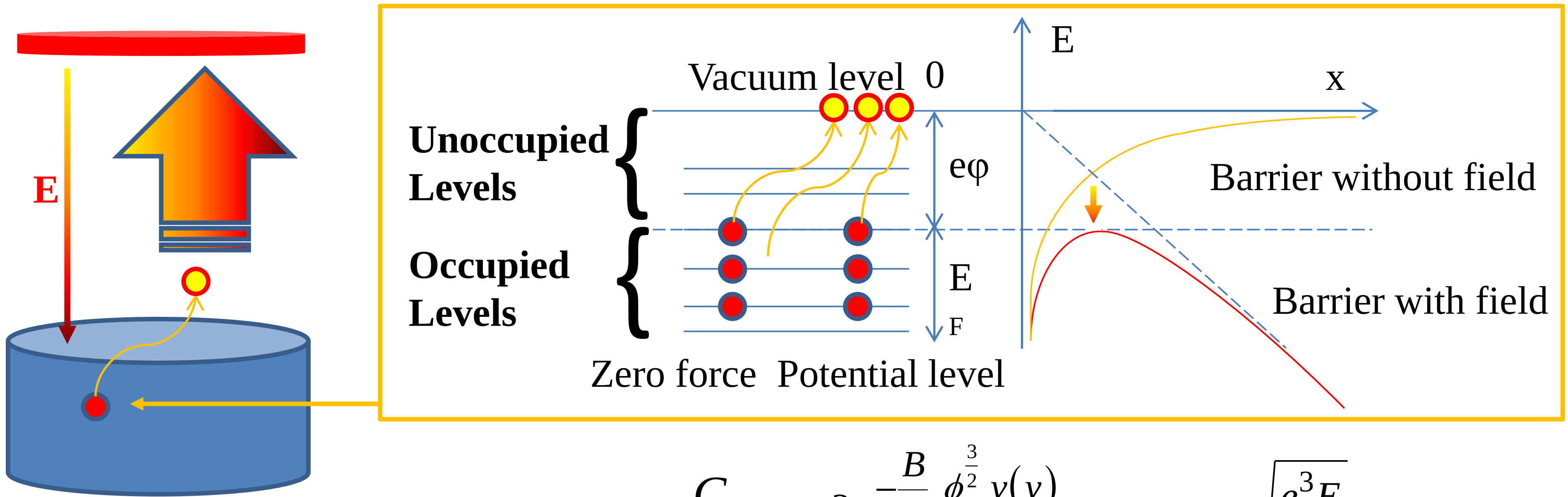
1. Thermionic emission, obeying the Richardson-Dushmann law: Thermal excitation allows free electrons reaching the vacuum level and escape the material.

2. Photo-electric emission obeying the Spicer Model: Photon absorption by the electron, Electron transport to the surface (electron scattering and phonon interaction with lattice atoms may reduce emission), Escape through the barrier (only electrons traveling toward the cathode surface, i.e. electron's momentum perpendicular to the surface can be emitted).

3. Field emission, following Fowler-Nordheim law: A very high fields (10^9 V/m or more) lowers the barrier in order to allow electrons quantum mechanically tunnel through the barrier.

Operative principles

CNT Cold Cathode: Field emission



Fowler-Nordheim Law

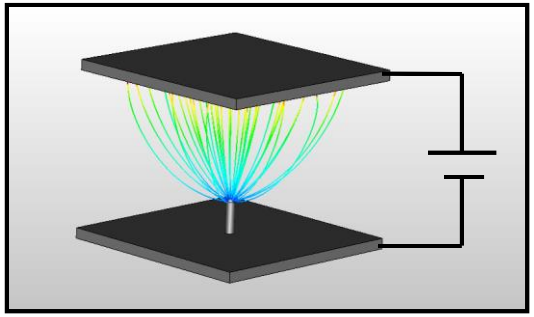
$$J = \frac{C}{\phi\ t^2(y)} E^2 e^{-\frac{B}{E}\phi^{\frac{3}{2}} v(y)} \qquad y = \sqrt{\frac{e^3 E}{\phi^2}}$$

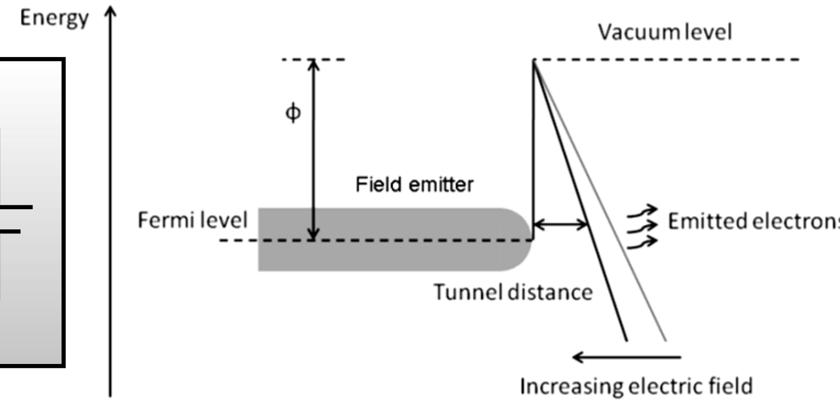
The electron source employed in this study is a carbon nanotube (CNT) emitter array. While an external electric field is applied, it changes the potential of cathode surface into a reduced potential barrier with a finite width. This effects is known as the Schottky effect. If the field is high enough, particles can tunnel through the barrier. This is called field emission and is regulated by the Fowler and Nordheim law where E is the applied electric field, Φ is the work function of the metal, C and B are constants of the material, and v(y) and t(y) are functions which arise due the inclusion of image charge effects and are near unity for typical conditions.

Operative principles

CNT Cold Cathode: Advantages of Cold Cathodes

- Working at ambient temperature
- Cathode patterning
- Small dimensions
- Possibility of modulate emitted current

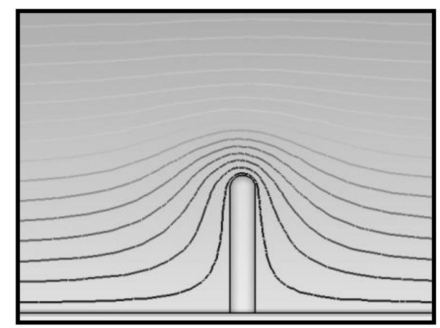




Fowler-Nordheim Law

$$J_{FN} = a \cdot \frac{\beta^2 \cdot E^2}{\phi} \cdot e^{\frac{-b \cdot \phi^{1.5}}{\beta \cdot E}}$$

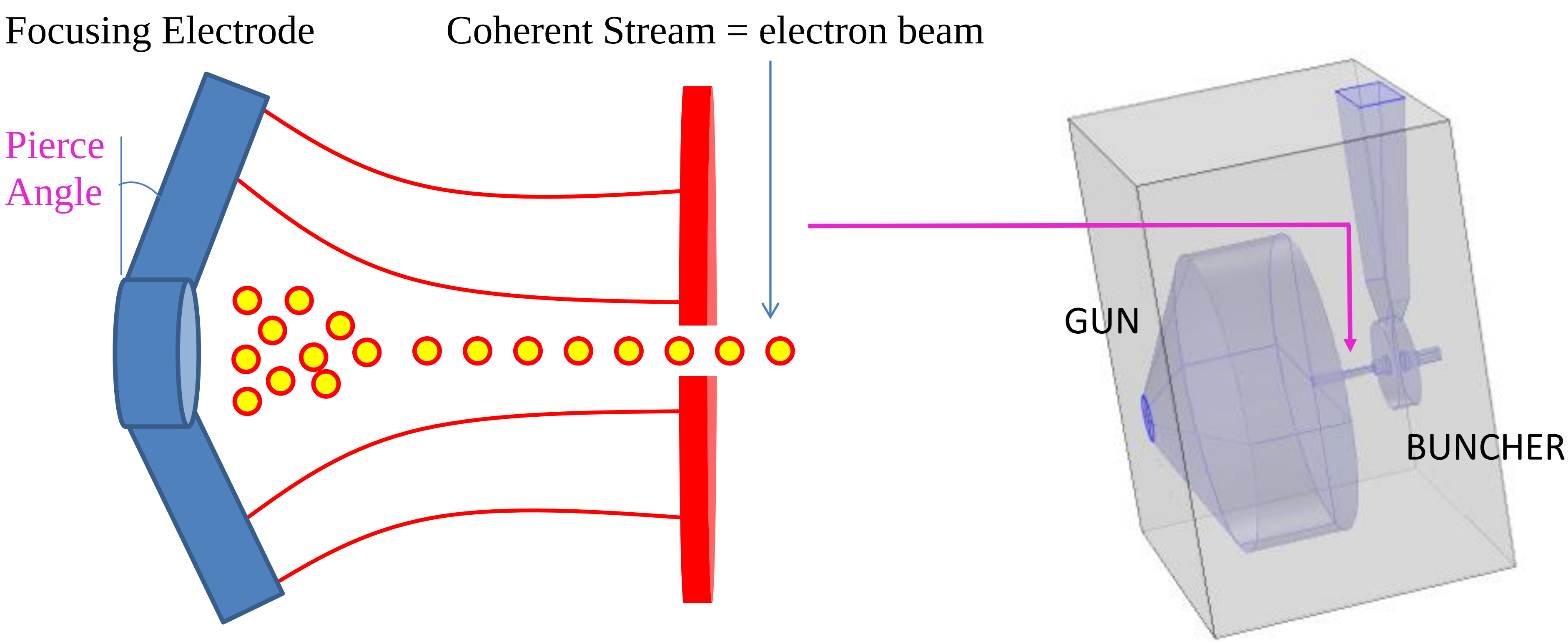
Field enhancement factor



The Fowler and Nordhiem function can be written isolating a multiplication factor, the Field Enhancement Factor β that can be increased by using carbon nanotubes. The main advantage of using cold cathode are the possibility of working at ambient temperature, the cathode patterning, small dimensions and the possibilility of modulate the emitted current

Operative principles

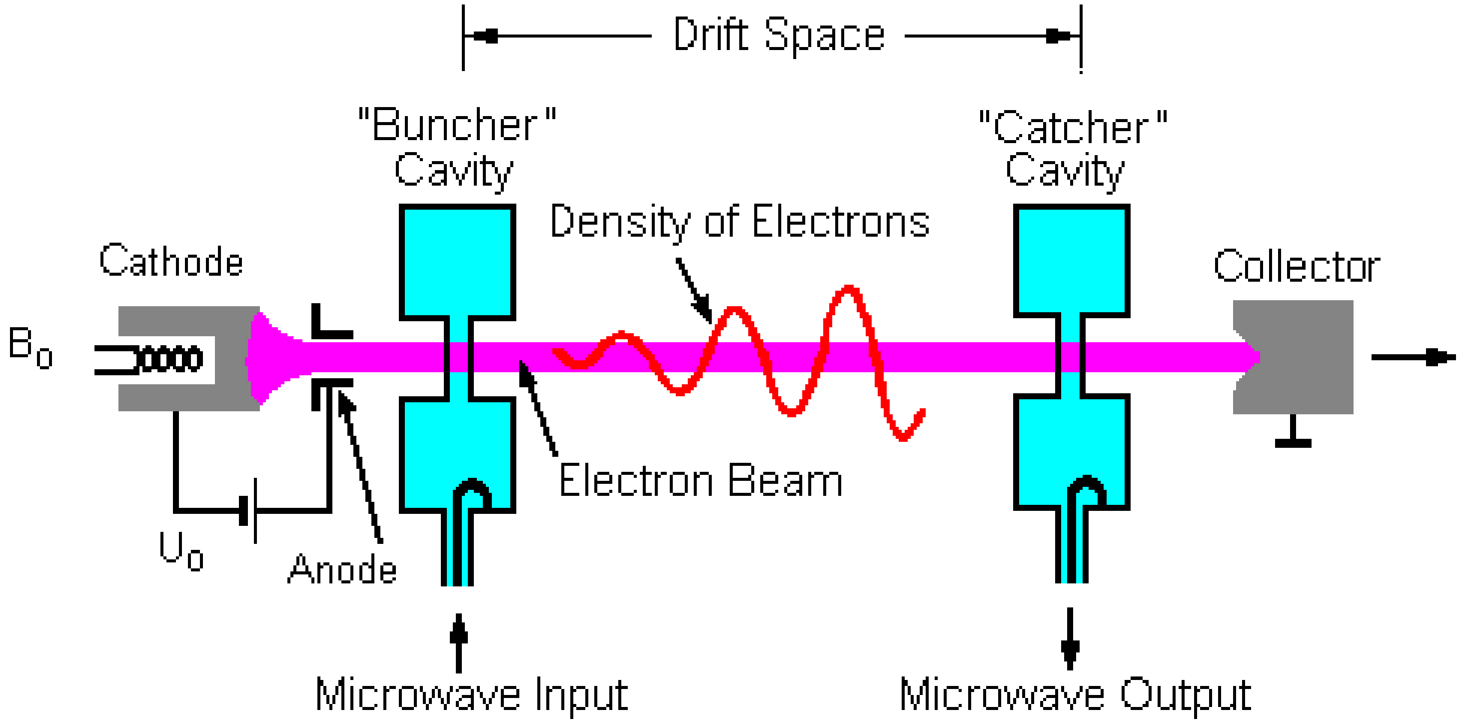
Vacuum Electron Gun



By opening a hole in the anode, electron can escape from the anode representing a coherent stream, the electron beam. A beam consists of particles with the same energy and direction (with a distribution). This beam can be employed in more complex electron tubes that need such a coherent stream as principal electron flux to manipulate.

Operative principles

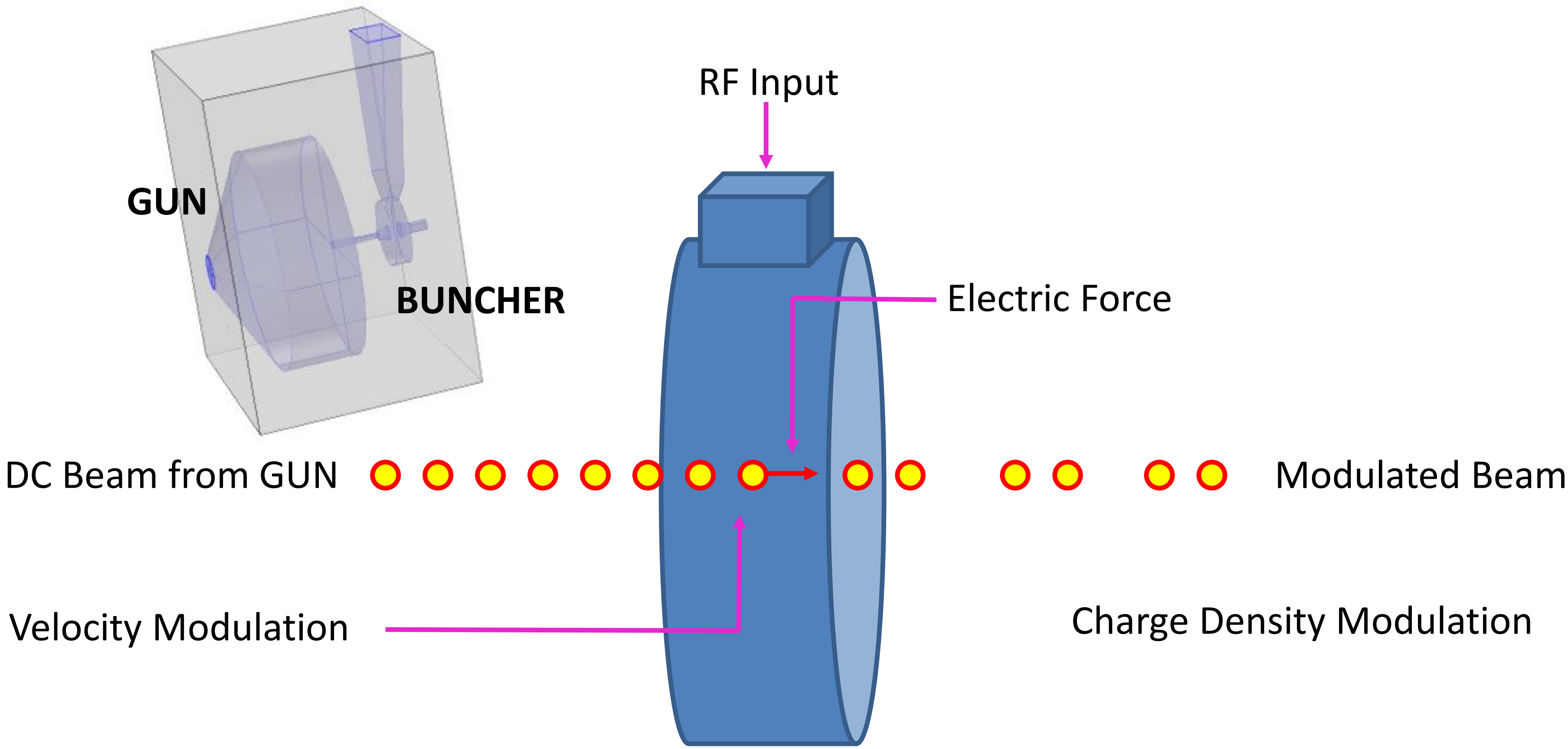
Klystron



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

Operative principles

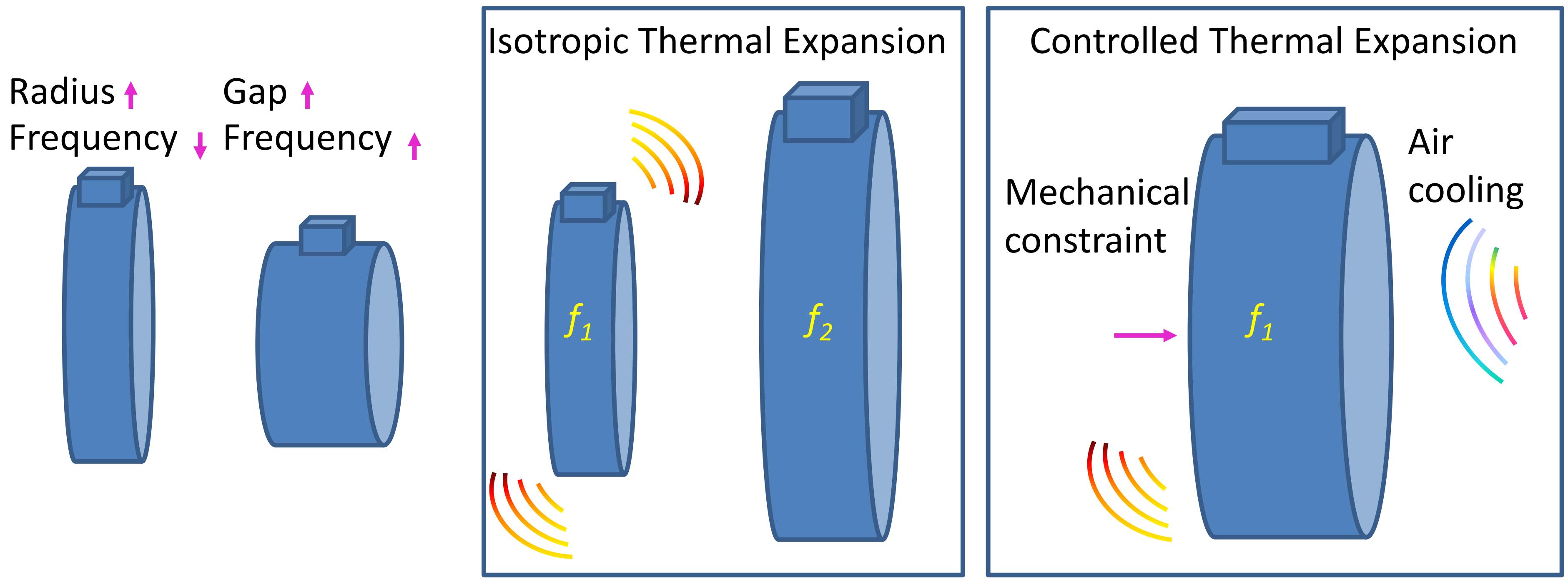
Buncher Cavity of the Klystron



The RF field produces the axial electric field in the Buncher to impress forces to the electrons, in order to modulate their velocity. Correct operation of the Buncher is ensured if it can use all the available power provided at the input to produce the desired axial electric field (bunching field). The Buncher needs to be critically matched to the RF source at the working frequency.

Operative principles

Thermal dependance of Frequency of Resonance



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 constraint and possible direction of thermal expansions have been considered, in order to obtain the desired compensation of the frequency lowering.

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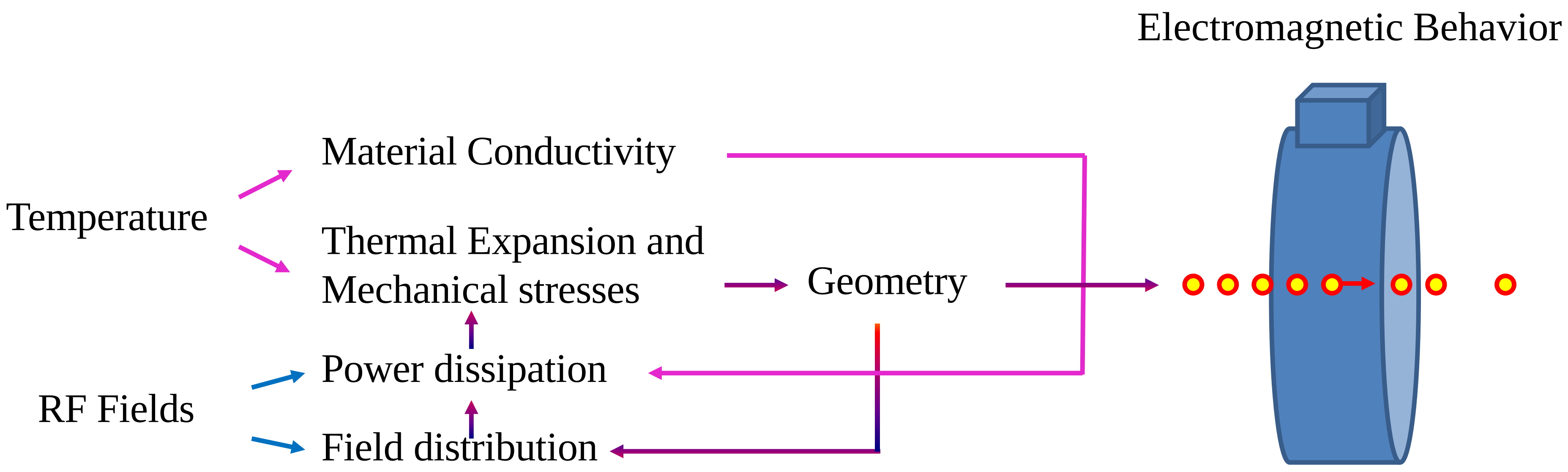
Motivations

Multiple Physics Influencing Factors

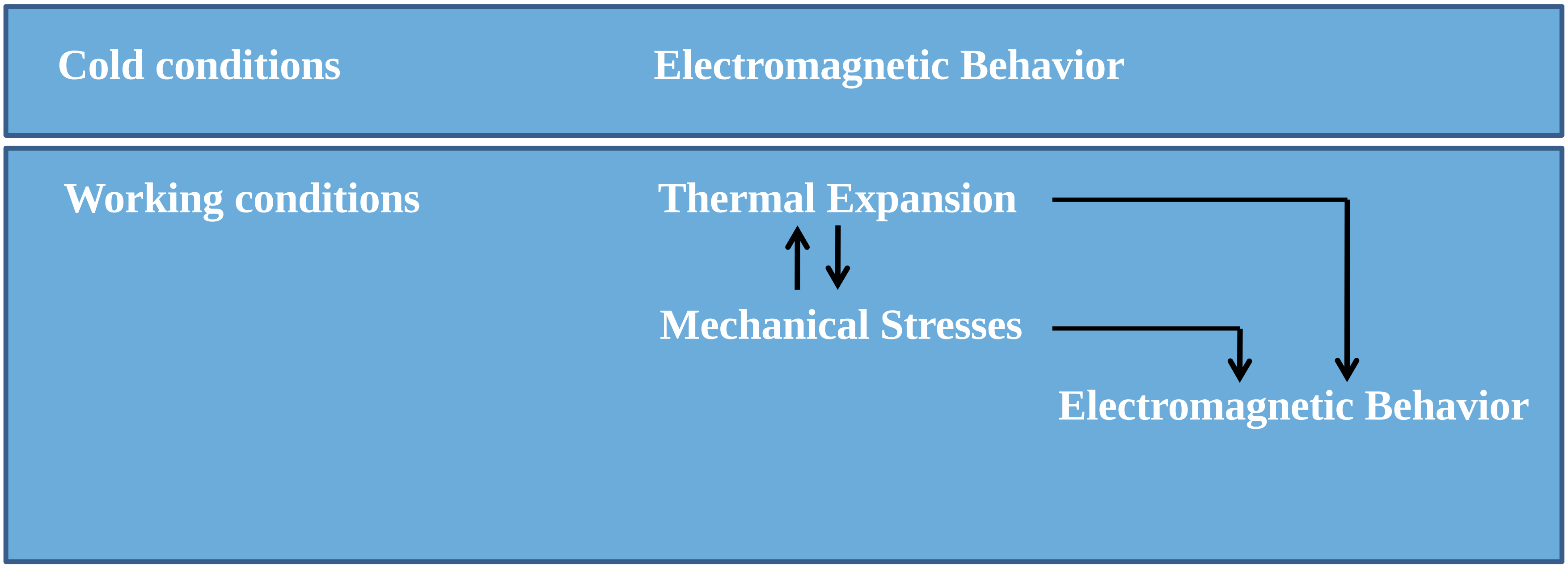


Critical operation in small dimension Range

An uncontrolled thermal expansion may produce destructive effects over the desired beam dynamics. 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.

Motivations

Multiphysics Simulation Ambient



The analysis follows a Multiphysics model approach, in order to prevent alterations of the electromagnetic (EM) behavior, while exposing the device to these multiple physics factors. 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.

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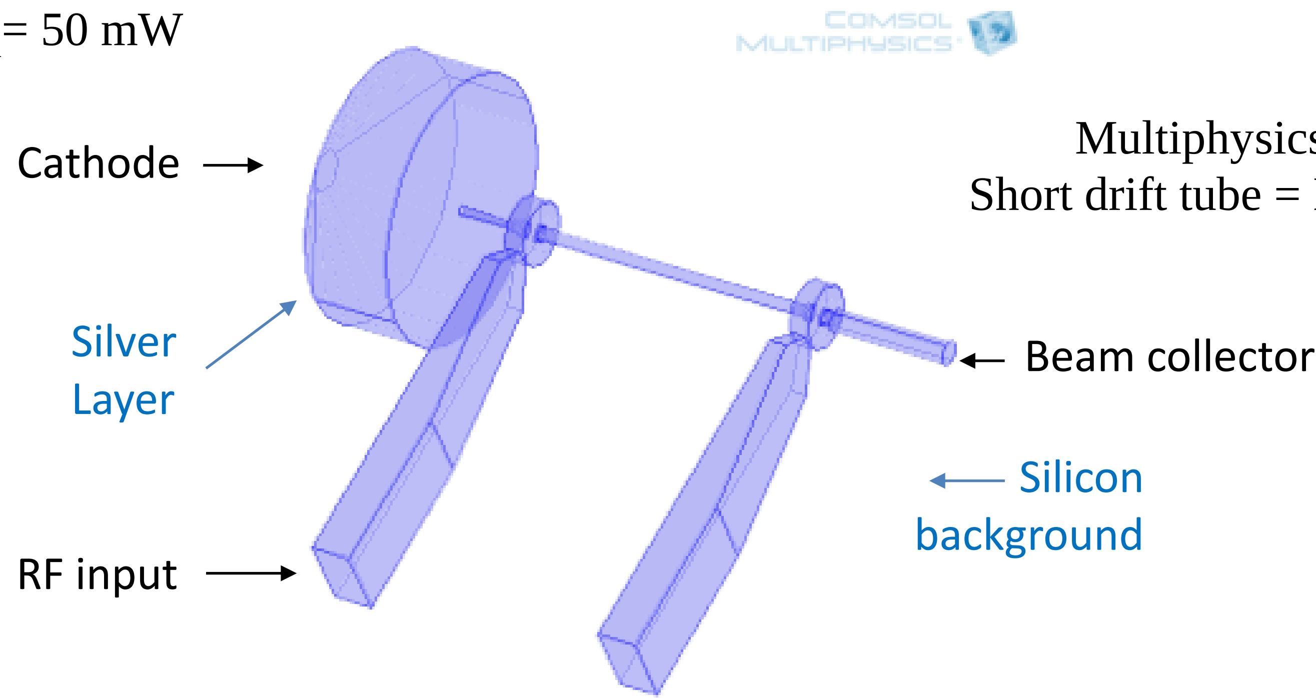
Klystron Features

Klystron Model

Electron Gun: I_b= 16 mA, E_b=10 keV, r_b=100μm

Cavities: f = 131.68 GHz, RL=21 dB, Z_S= 342.5 kΩ

P_{in}= 50 mW



Multiphysics Worst case
Short drift tube = High temperature

The solid material is a block of Silicon at which interior, the vacuum region of electron gun, Buncher, drift tube and catcher is present. A layer of Silver is deposed on the internal surfaces except for the circular lateral surface of the gun that insulate the anode to cathode. Anode and cathode are made of molybdenum; the interaction region is made of non-ideal vacuum (air at 10^{-7} bar).

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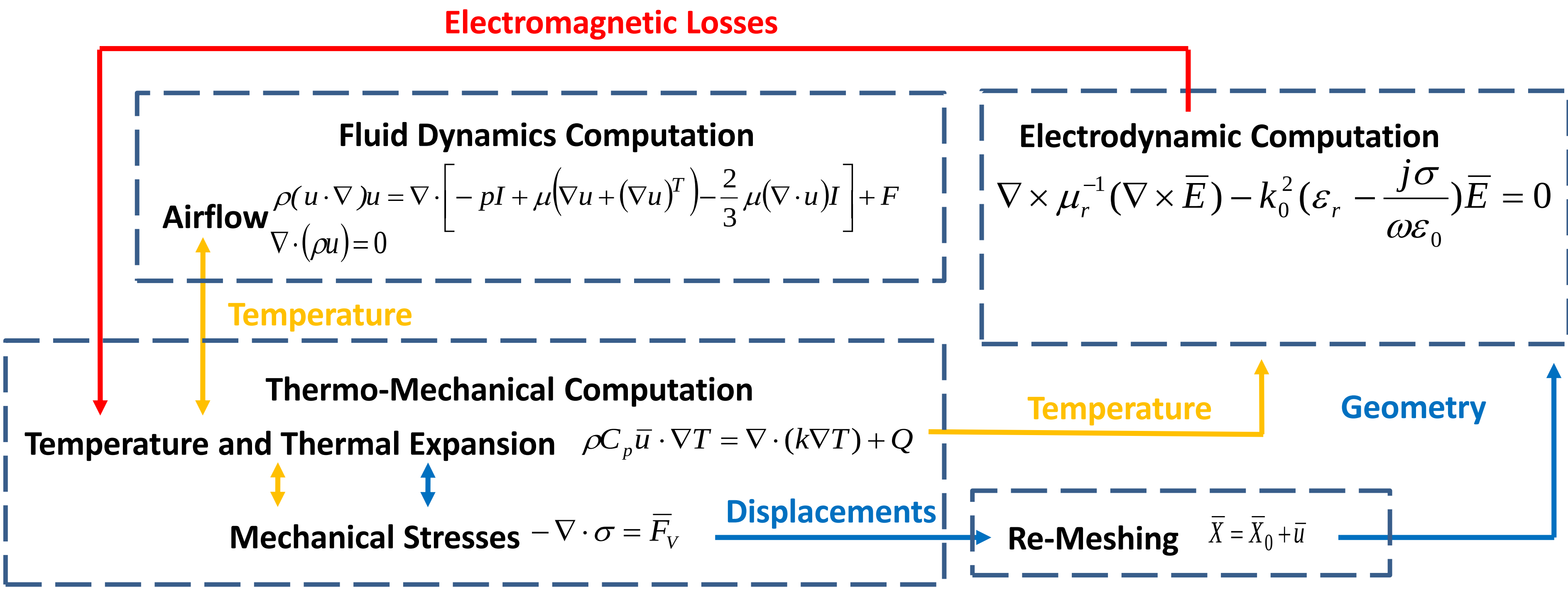
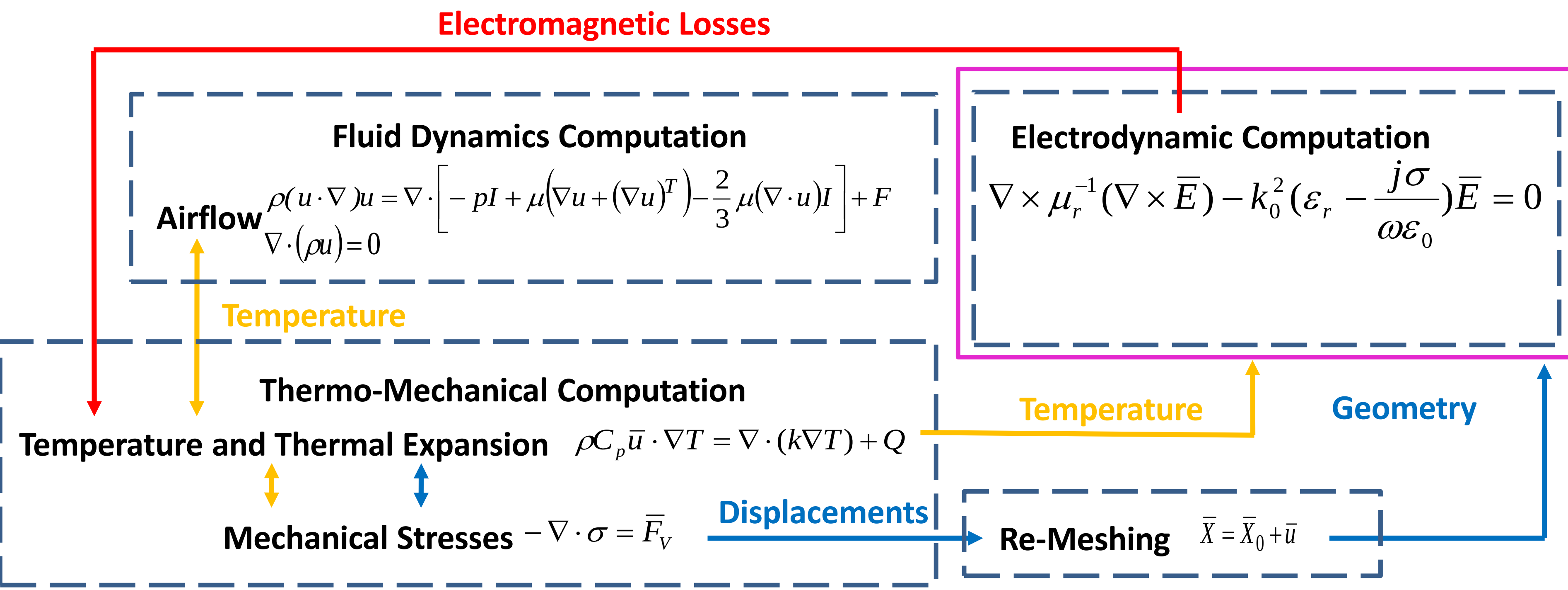
Numerical model



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.

Numerical model



The preliminary **EM analysis** is the first step. It has been employed to calculate the microwave power dissipations when wall current flows on the cavity walls while it receives the operative input signal (50 mW mean power) at the input port and emits output signal (2W) at the output port. This power dissipation has been prescribed into the thermodynamic calculation as a heat power source.

Numerical model

Electromagnetic Analysis

Multiphysics Simulation Ambient

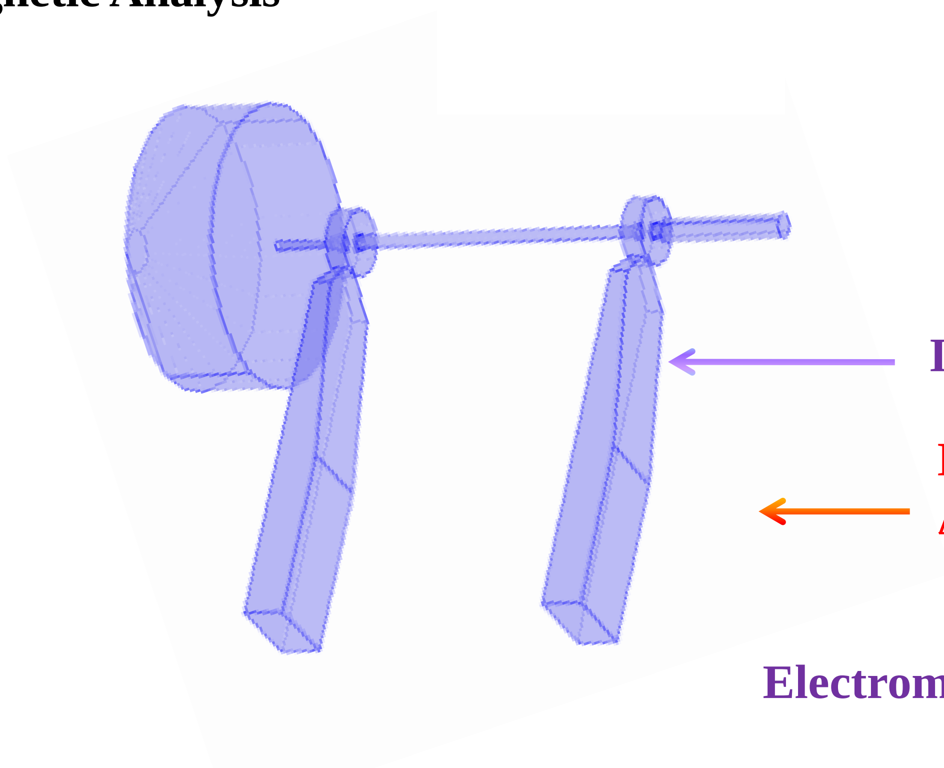
Electromagnetic Analysis

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

In the formula: μ_r is the relative magnetic permeability, ε_r the relative electrical permittivity and σ the electrical conductivity of the material ($S \cdot m^{-1}$); ε_0 is the electrical permittivity of the vacuum ($F \cdot m^{-1}$), k_0 the wave number in free space (m^{-1}), ω the wave angular frequency (s^{-1}) and the electric field ($V \cdot m^{-1}$).

Numerical model

Electromagnetic Analysis



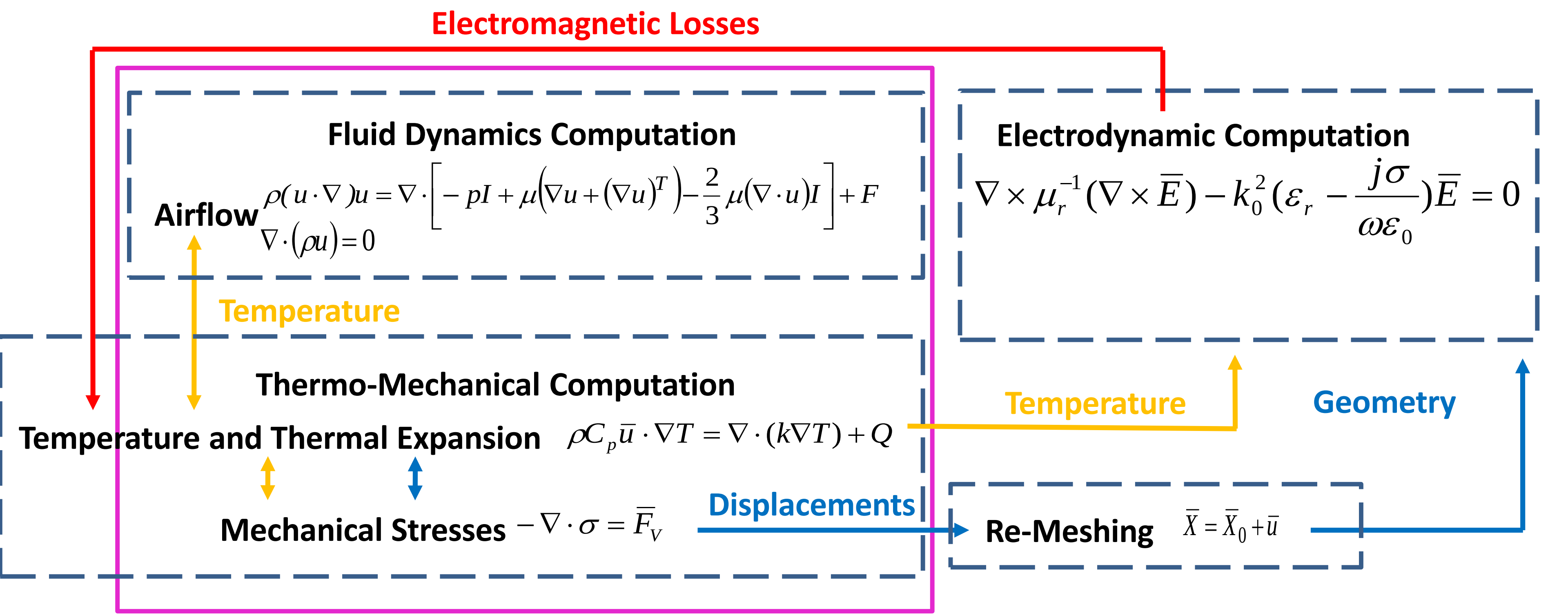
Impedance Boundary Condition

INPUT:
Ambient Temperature

Electromagnetic Loss calculation

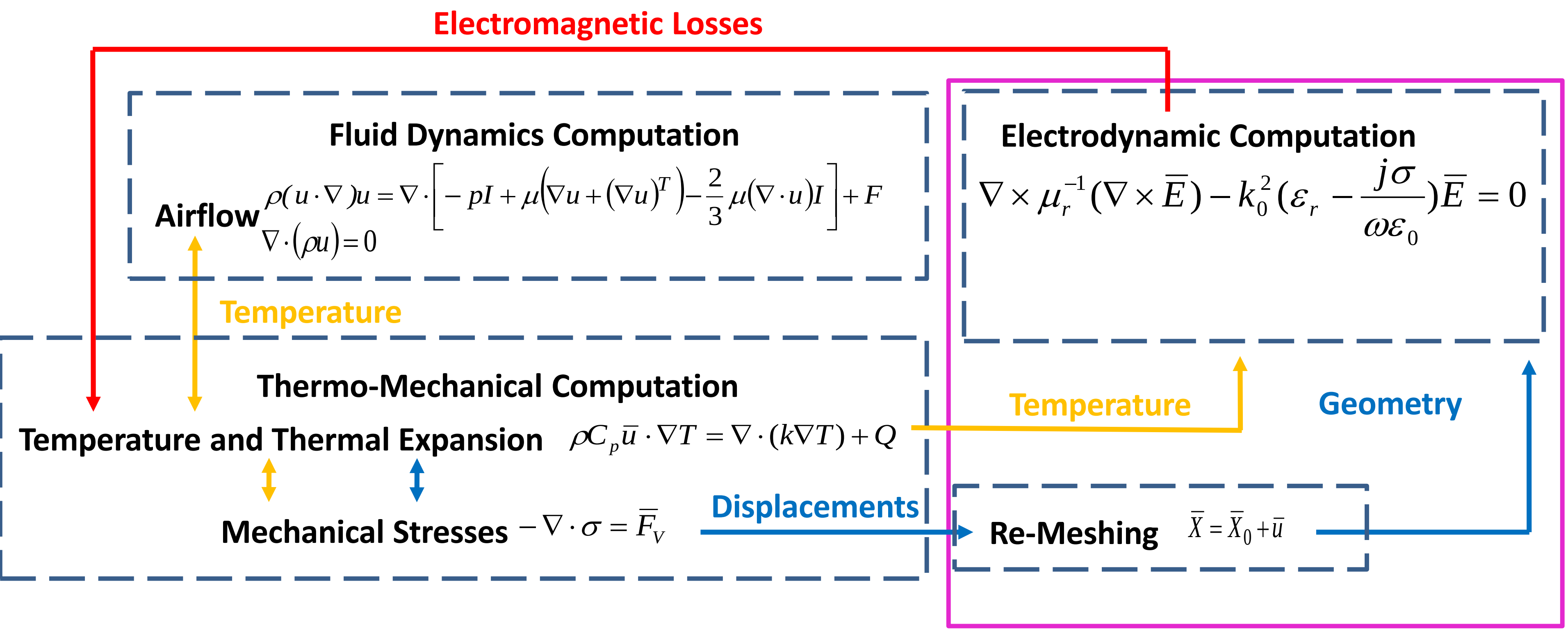
Impedance boundary condition: The surfaces, shared between vacuum and the supporting solid material, are modeled in order to consider the losses due to the partial penetration of the electric field in the lossy material which constitutes such walls. This condition allows to exclude a further domain to the EMW calculation, avoiding the meshing and saving computational cost. The specified thickness of the wall boundaries is fixed to 80μm. Electric conductivity is determined considering its thermal dependence basing on material properties.

Numerical model



Thermo-mechanical with Fluid Dynamics Computation is the second step. The heat is computed in the whole volume, receiving in input the temperature on the emitting surface of the cathode (which is a figure of merit of the employed cathode).

Numerical model



A **Re-meshing** of the geometry is performed: The displacements have been employed to obtain a deformed geometry by Moving Mesh (MM) dedicated interface.
Electromagnetic analysis is the last step. It has been executed on the new meshes receiving the temperatures evaluated by the TD and FD studies.

Numerical model

Thermo-mechanical and Fluid Dynamics Computation

Multiphysics Simulation Ambient

Fluid Dynamics Analysis

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

Thermo-mechnical Analysis

$$\nabla\cdot(\rho u)=0$$

Fully coupled Stationary

Thermodynamic

$$\rho C_{p}u\cdot\nabla T=\nabla\cdot(k\nabla T)+Q$$

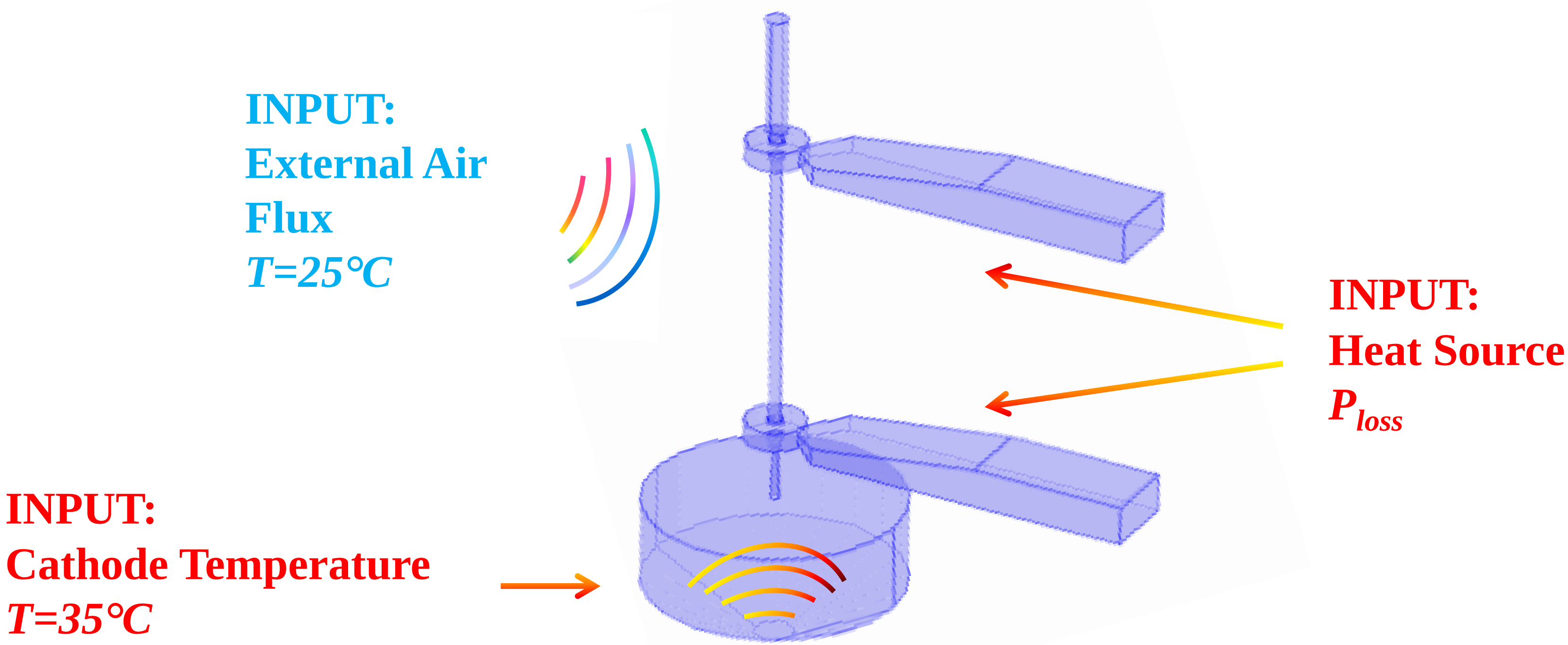
Structural Mechanics

$$-\nabla\cdot\sigma=F$$

In the formulas: p is the pressure, μ the dynamic viscosity (Pa·s) of the material (the air) and F 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 **Text = 20°C**, σ is the stress ; ρ is the density, C_p the heat capacity at constant pressure, and *k* the thermal conductivity of the material. *T* is the temperature computed on the surfaces, *Q* is the heat source, *u* is the velocity field vector.

Numerical model

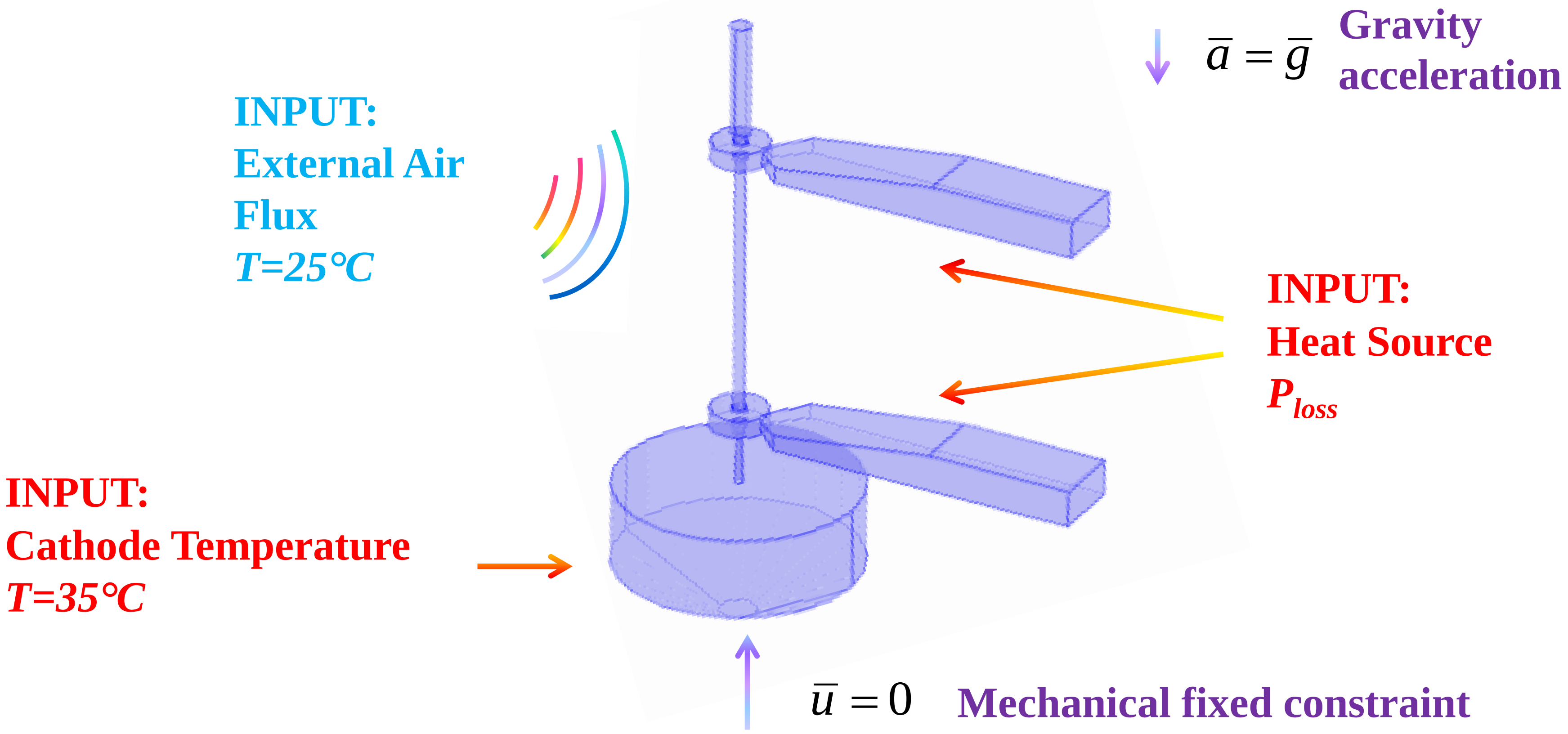
Thermo-mechanical and Fluid Dynamics Analysis



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. The external environment temperature is T_{ext} = 20°C, consistently with a typical environment temperature condition. The cathode surface has been considered at its nominal operative temperature that is **35°C**. The power dissipation calculated in a preliminary Electromagnetic analysis has been prescribed on the Buncher walls as surface density power source.

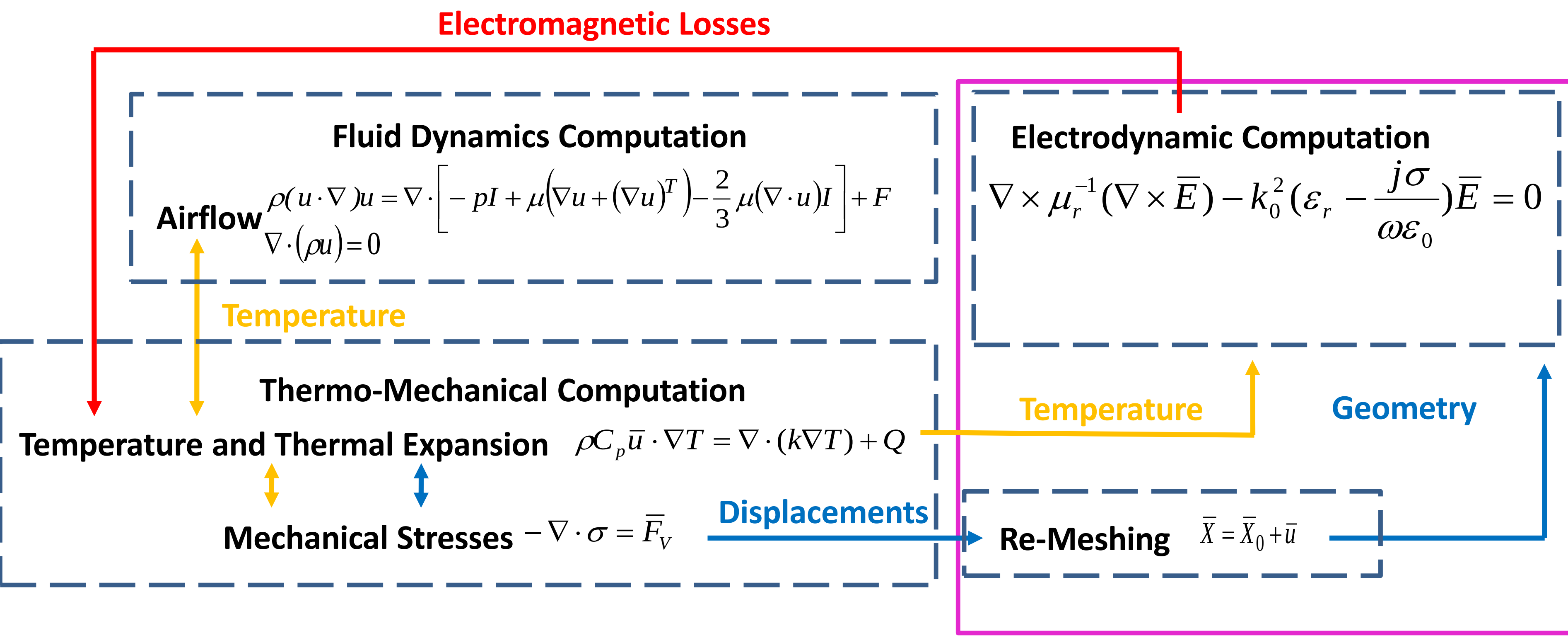
Numerical model

Thermo-mechanical and Fluid Dynamics Analysis



The external base surface of the cathode is locked to rigid structures in order to support the device. Thus, represents a mechanical fixed constraint. Gravity acceleration has been also considered.

Numerical model



A **Re-meshing** of the geometry is performed: The displacements have been employed to obtain a deformed geometry by Moving Mesh (MM) dedicated interface.

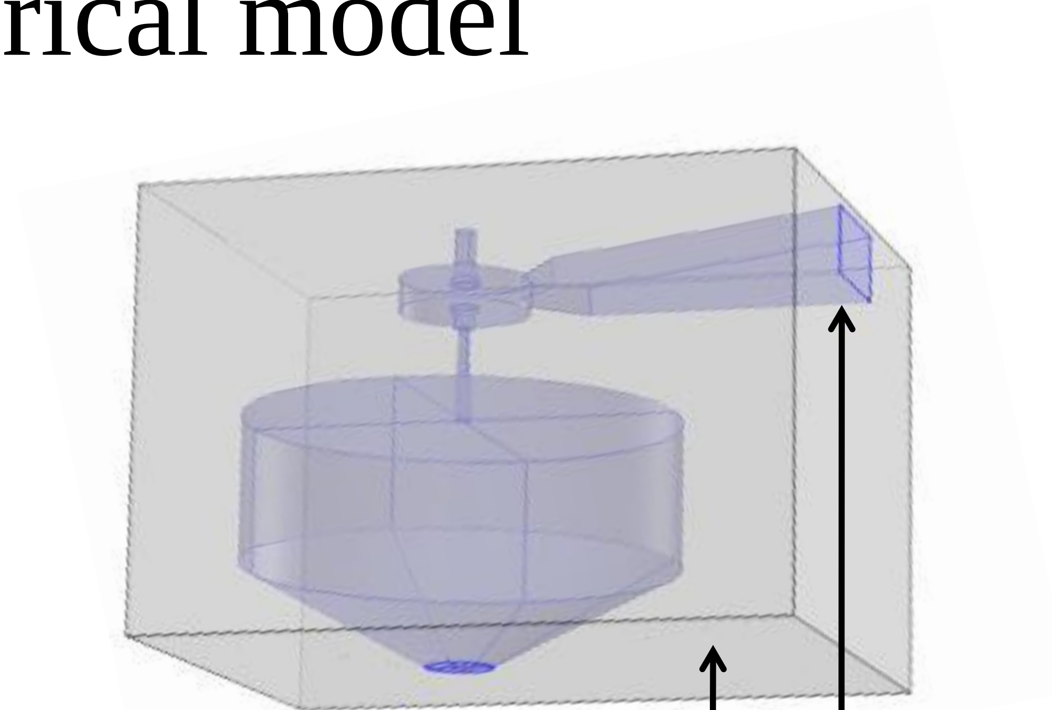
Electromagnetic analysis is the last step. It has been executed on the new meshes receiving the temperatures evaluated by the TD and FD studies.

Numerical model

Mesh displacement computation

Applied to the whole structure.

$$\overline{X} = \overline{X}_0 + \overline{u}$$



From TM

Volume prescribed Deformation → Silicon background

Volume Free Deformation → Non ideal vacuum

Surface Prescribed Mesh Displacement → Surfaces shared with background and the non ideal vacuum volume

Prescribed deformation: The structure of the Klystron represent the volume subjected to deformation. The displacement vectors (u, v, w) computed by the SM module are employed to specify this volumetric deformation. Free deformation: The non ideal vacuum and air volumes (which are not subjected to any structural elastic formulation by the SM analysis) are free to move. Mesh Displacement: This condition specifies that the surface boundaries shared between the volumes subjected to deformation and the ones free to move need to be deformed by the SM computation.

Numerical model

Electromagnetic Analysis

Multiphysics Simulation Ambient

Electromagnetic Analysis

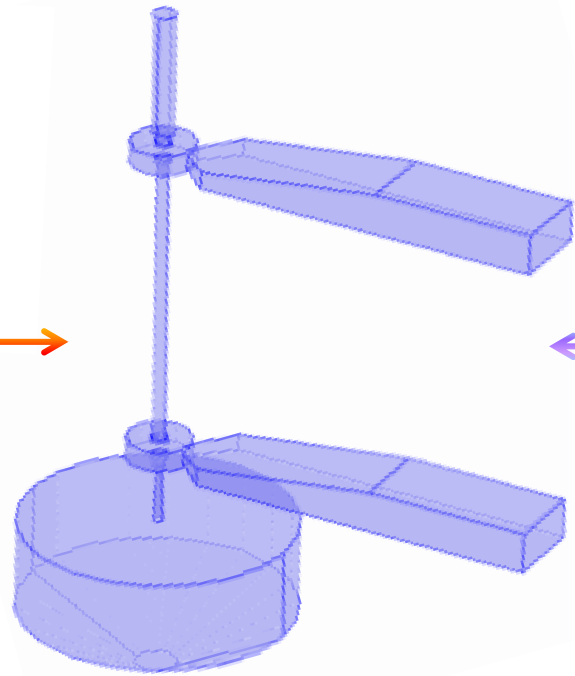
$$\nabla \times \mu_r^{-1}(\nabla \times \bar{E}) - k_0^2(\varepsilon_r - \frac{j\sigma}{\omega\varepsilon_0})\bar{E} = 0$$

In the formula: μ_r is the relative magnetic permeability, ε_r the relative electrical permittivity and σ the electrical conductivity of the material (S·m^{-1}); ε_0 is the electrical permittivity of the vacuum (F·m^{-1}), k_0 the wave number in free space (m^{-1}), ω the wave angular frequency (s^{-1}) and the electric field (V·m^{-1}).

Numerical model

Electromagnetic Analysis

INPUT:
Temperature from TM Computation



Impedance Boundary Condition

Scattering Parameters and Electric Field Calculation

Impedance boundary condition: The surfaces, shared between vacuum and the supporting solid material, are modeled in order to consider the losses due to the partial penetration of the electric field in the lossy material which constitutes such walls. This condition allows to exclude a further domain to the EMW calculation, avoiding the meshing and saving computational cost. The specified thickness of the wall boundaries is fixed to 80μm. Electric conductivity is determined considering its thermal dependence basing on material properties.

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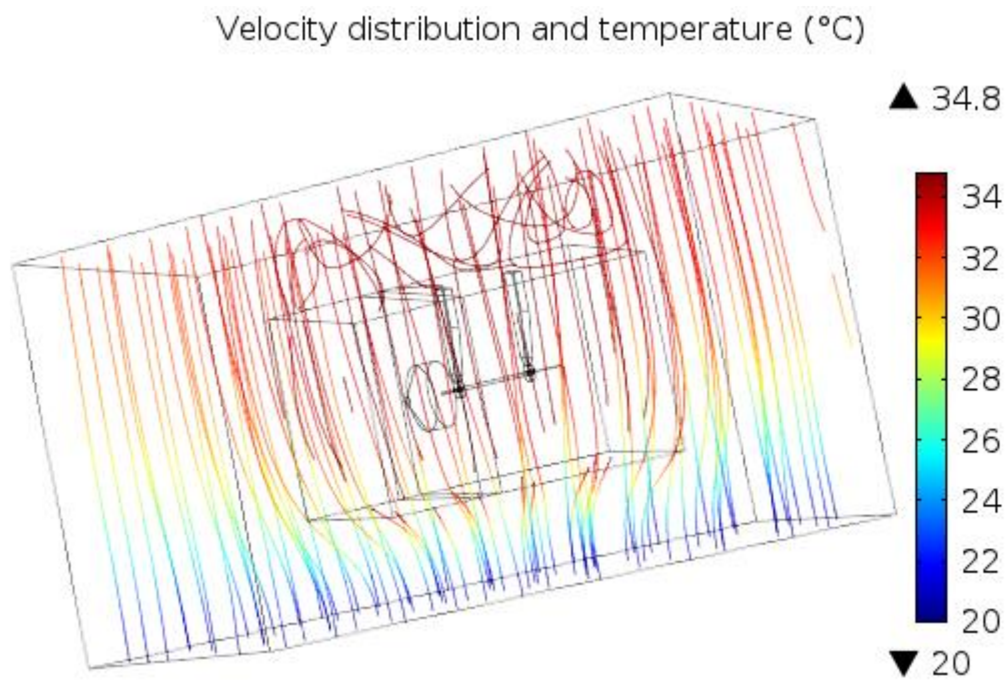
Simulation Results

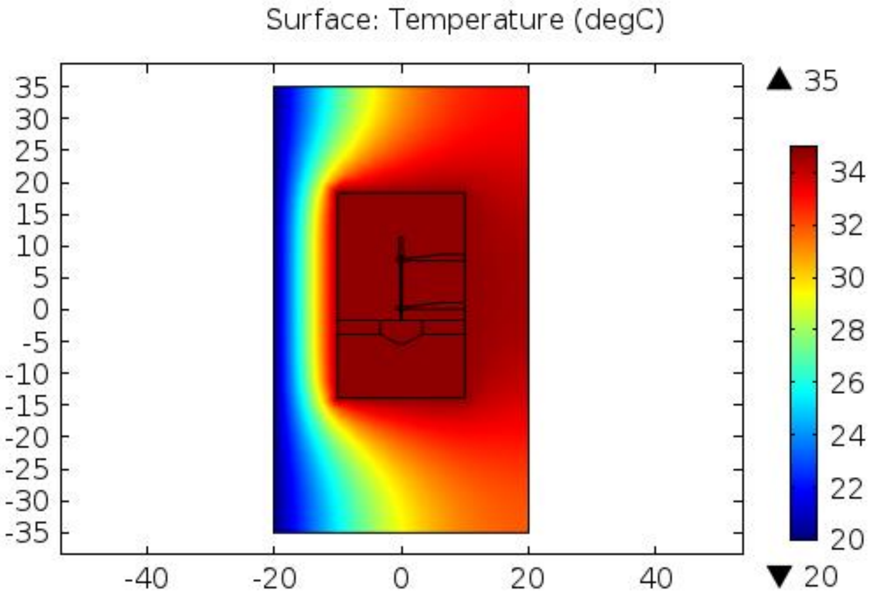
Thermomechanical features

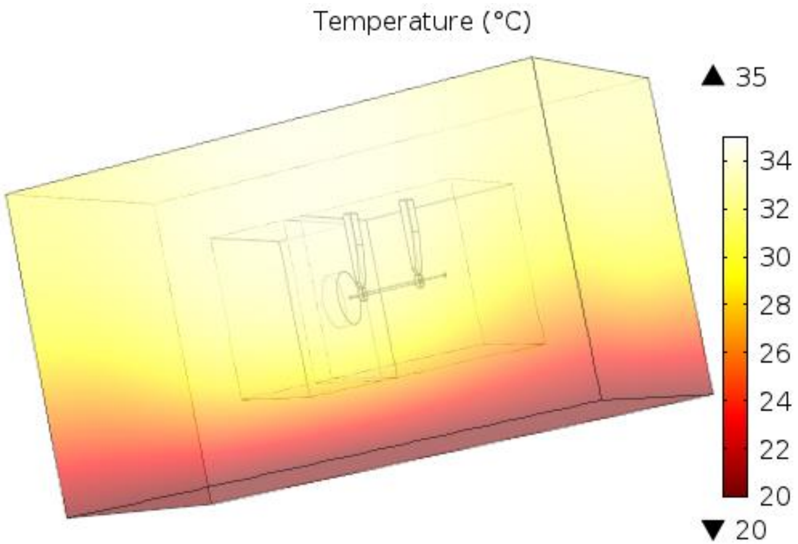


While the airflow enters the box, it is at this temperature, and then by exchanging heat with the device external surface, it becomes warmer approaching to a maximum temperature of 34.8°C, when it hits the device. This is the needed effect that allows to contain the dilation of the cavity radius.

Simulation Results

Thermomechanical features

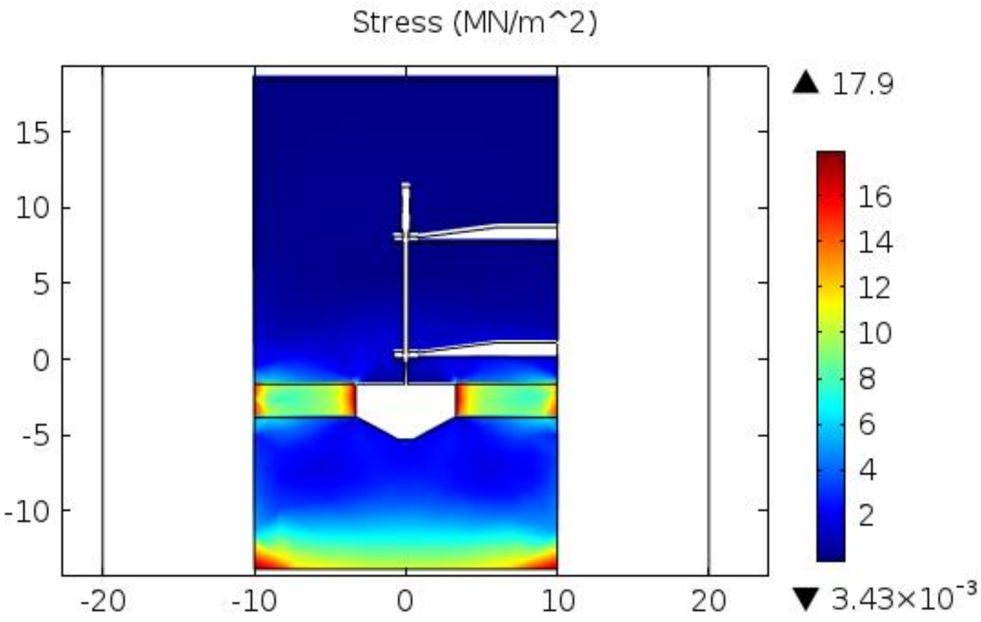


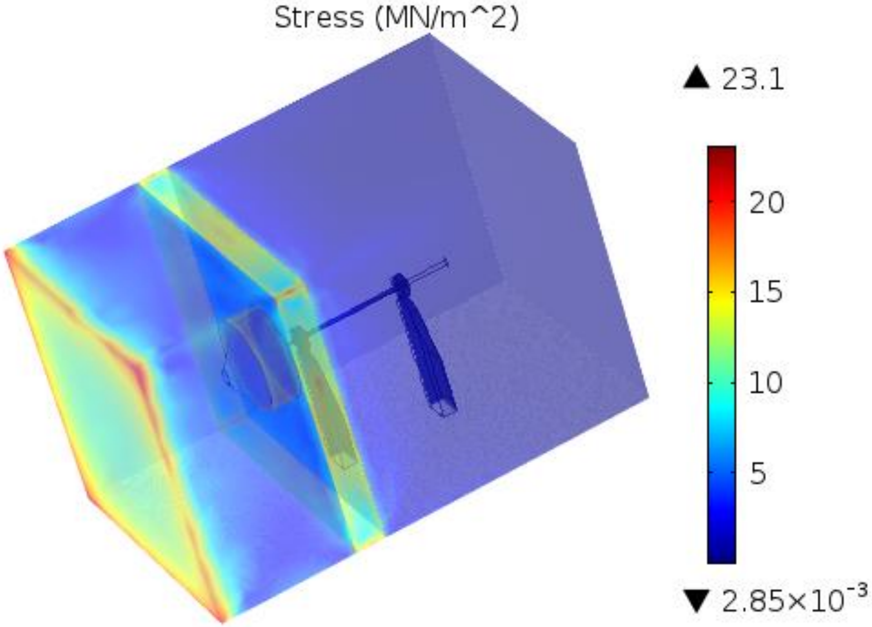


The maximum temperature reached internally is 35°C. This is due to the cathode operative temperature at the lower surface.

Simulation Results

Thermomechanical features

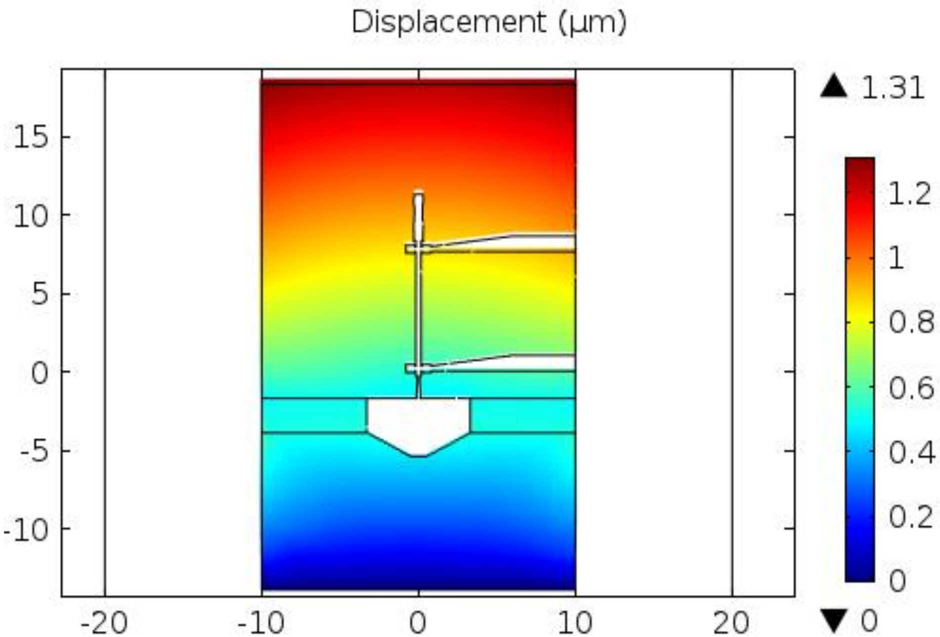


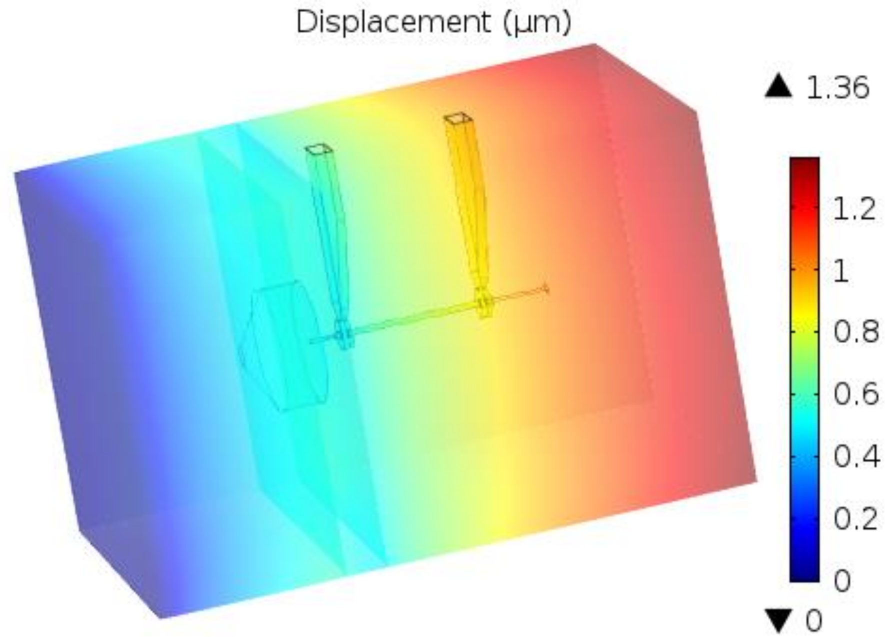


The maximum stress is about 23.1 MNm^{-2} located at the edges of the warmest face which is fixed to the rigid support. This is due to the high stiffness of silicon that counteracts the binding forces at the fixed surface.

Simulation Results

Thermomechanical features

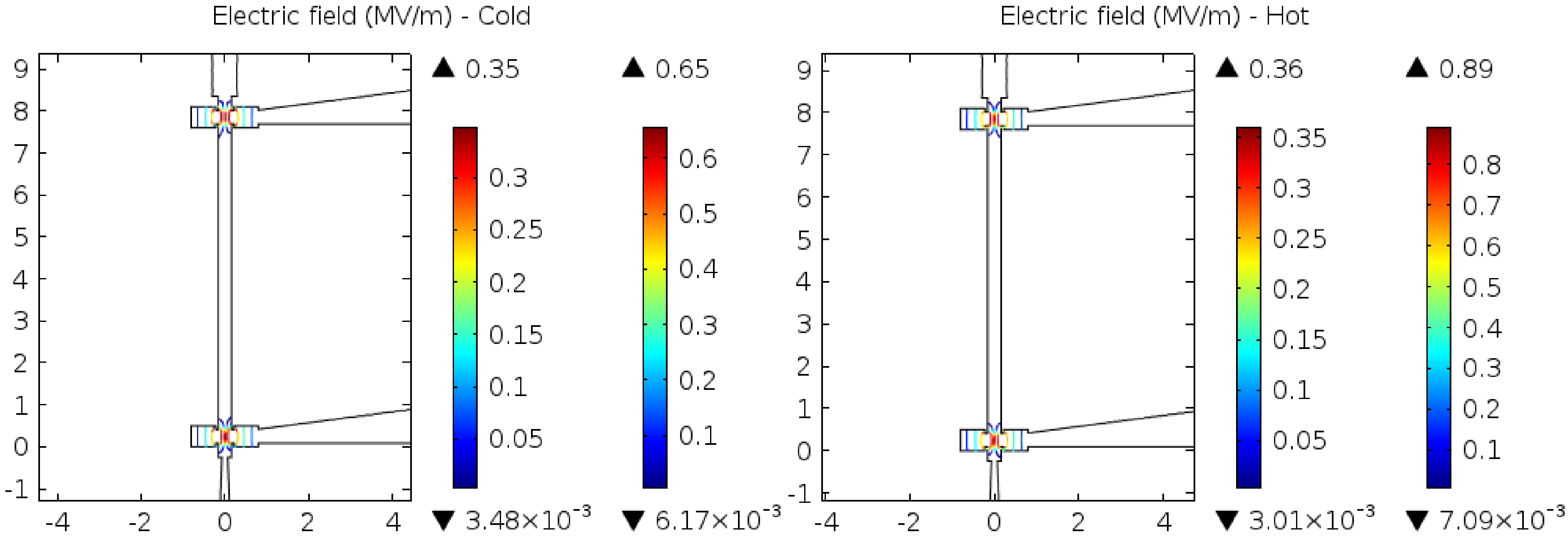




The internal shape, more free to deform, is less stressed, farther from which, the maximum total displacement is and is about 1.31 µm (due to the low thermal expansion of silicon). It can be also noted the achievement of the desired displacement: More displacement is directed along the axial direction *z* and less along the radial direction *x*.

Simulation Results

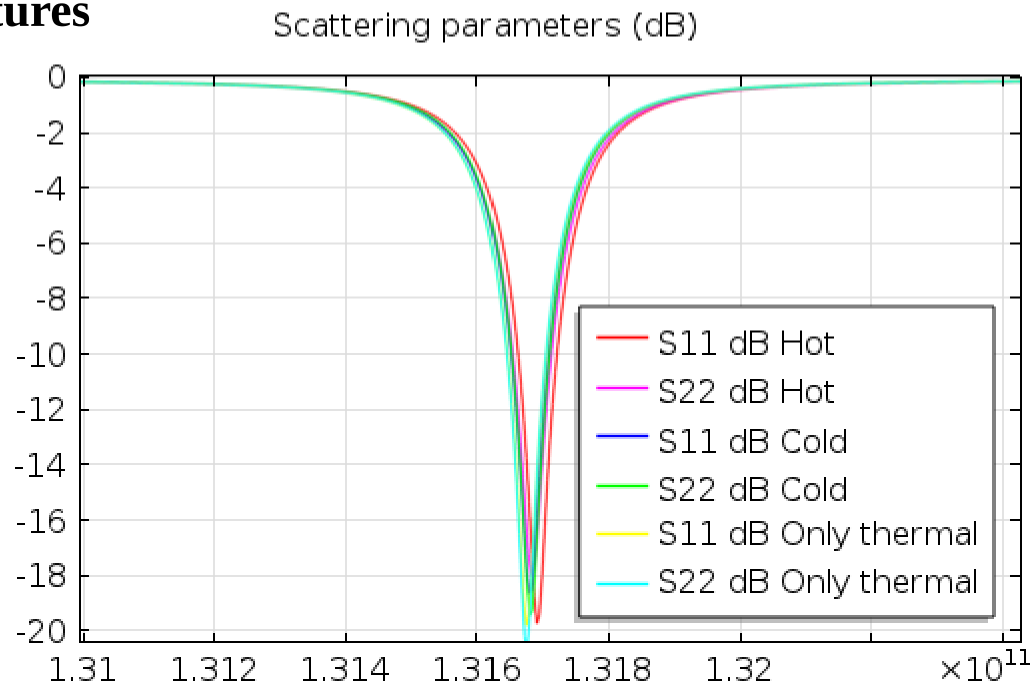
Electromagnetic Features



The streamline distribution of the electrodynamics fields for the bunching along the central plane are reported. While receiving 50mW at the input, the axial electric field inside the Buncher reaches a maximum m value of $E_{ACmax} = 0.35$ MVm^{-1} in cold condition and $E_{ACmax} = 0.36$ MVm^{-1} thermo-mechanical conditions. While producing 2 W output power, the Catcher reaches in cold conditions $E_{ACmax} = 0.65$ MVm^{-1} and in thermo-mechanical operating conditions $E_{ACmax} = 0.89$ MVm^{-1}It can be noted that these fields are distribute in the pattern of the desired resonant mode, the quasi TM_{010} expected

Simulation Results

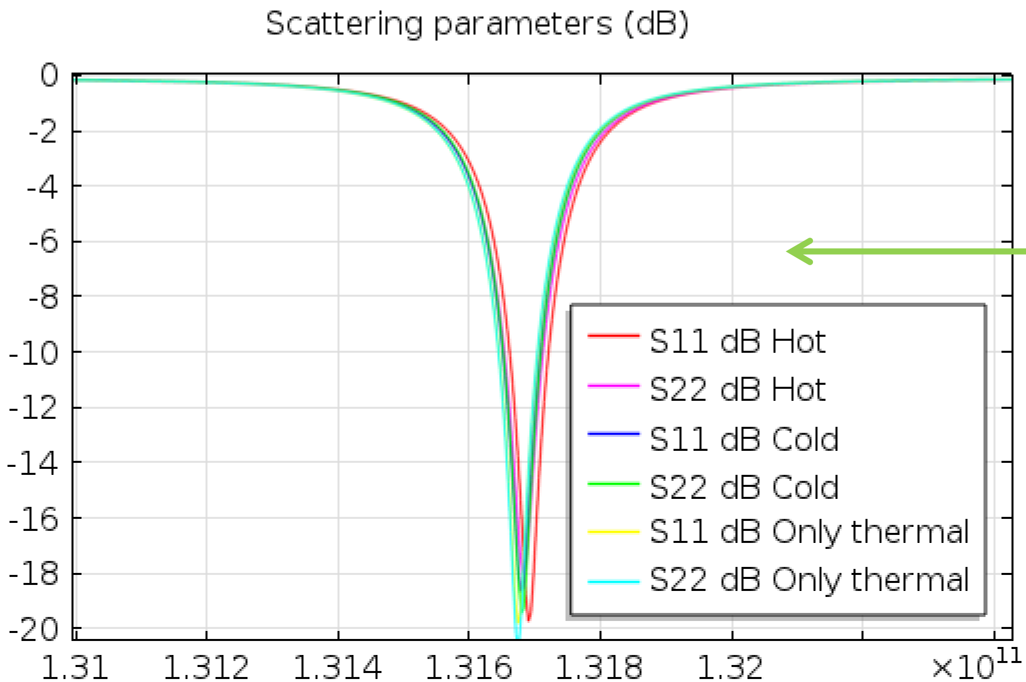
Electromagnetic Features

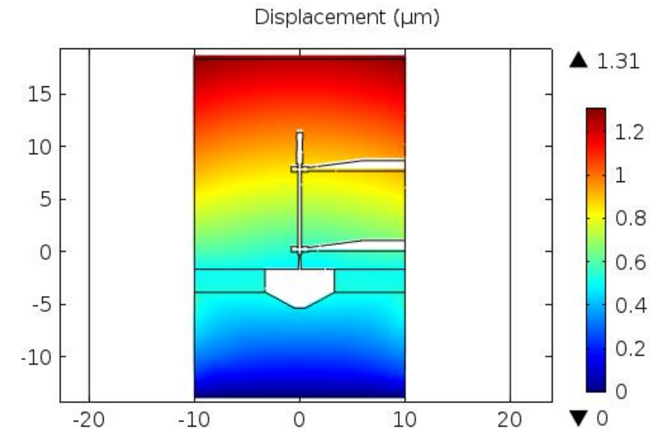


Scattering parameters in cold and in TM operating conditions have been documented. In this analysis has been considered also the case of the sole computation of thermal condition without considering thermomechanical induced deformation. The resonance frequency of the Buncher from the cold condition (where it has the value of f_1=131.68 GHz, blue curve) decreases to f_2 = 131.67 if only the thermodynamic condition is considered. The same value is obtained for the Catcher. By considering thermomechanical displacement, the frequency is increased due to the gap dilation. In this condition, the Buncher resonance frequency moves to f_3=131.69, while the Catcher frequency remains at 131.68 GHz.

Simulation Results

Electromagnetic Features



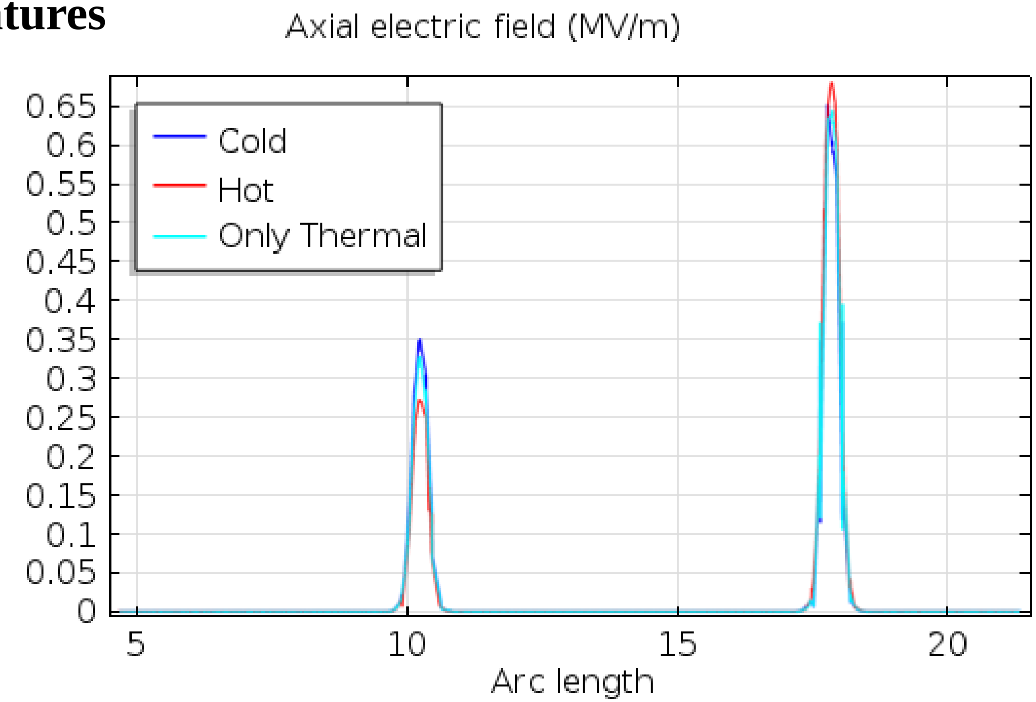


While the cooling air flux is operating, the controlled temperature at cavities lateral surfaces contains shape alteration. Anyhow, the base surface, where the beam output hole is located, cavity tends to expanse straightly, since is less refrigerated, due to the positioning of the air flux streamlines which are crossed to longitudinal axis. This effect allows for a frequency increase.

The insertion loss of the Buncher increases from 18.6 to 19.6dB but the insertion loss of the Catcher decrease from 19.4 to 18.0 db.

Simulation Results

Electromagnetic Features



The longitudinal distribution of the electrodynamics fields in cold and in thermo-mechanical conditions are reported. While receiving 50mW at the input, the axial electric field inside the Buncher reaches a maximum m value of E_{ACmax} = 0.35 MVm^{-1} in cold condition and E_{ACmax} = 0.36 MVm^{-1} thermo-mechanical operating conditions. However, at the center of the cavity it decrease slightly from $E_{AC(r=0)}$ = 0.35 MVm^{-1} (that, in this case, it corresponds with the maximum amplitude in the Buncher) to $E_{AC(r=0)}$ = 0.27 MVm^{-1} in thermomechanical condition. While producing 2 W output power, the Catcher reaches in cold conditions E_{ACmax} = 0.65 MVm^{-1} and in thermo-mechanical operating conditions E_{ACmax} = 0.89 MVm^{-1} but at the center of the Catcher, from $E_{AC(r=0)}$ = 0.65 MVm^{-1} it becomes $E_{AC(r=0)}$ = 0.68 MVm^{-1}.

Outline

- Introduction
- Operative principles
- Motivations
- Klystron Features
- Numerical model
- Simulation Results
- Conclusions

Conclusions

The **Multiphysics design of a 130 GHz klystron** is described in this presentation. In order to reduce thermal expansion of the material typical of the classical thermionic cathodes, a Carbon nanotube cold cathode is employed.

A multiphysics design approach has been employed to ensure the future correct operation: **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**.
Scattering parameters at the input port and **axial electric field** of the cavities have been calculated.

As demonstrated from this model, the silicon background material using cold cathode and cooling airflow **inhibits destructive thermal effects**.

In this study, 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**.

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Thank You !

Multiphysics Design of a 130 GHz Klystron

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