

Key-Holes Magnetron Design and Multiphysics Simulation

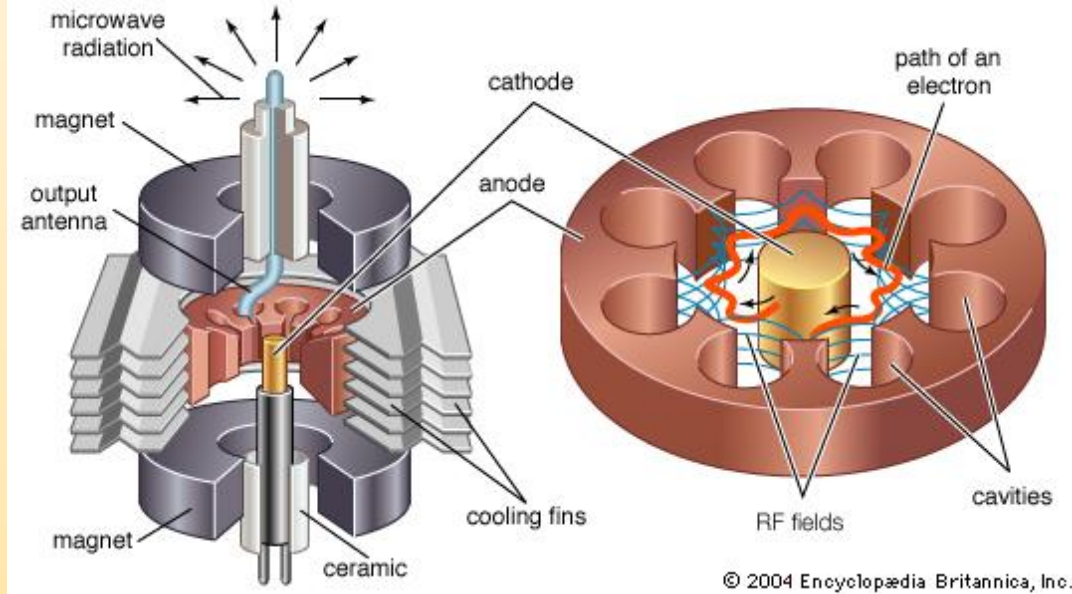
*Alberto Leggieri, Franco Di Paolo,
Davide Passi*

Department of Electronic Engineering
University of Roma "Tor Vergata"
00133 Roma Italy, email alberto.leggieri@uniroma2.it

Outline

- Microwave Magnetron
- Motivations
- Proposed Magnetron Features
- Use of COMSOL Multiphysics
- Simulation Results
- Conclusions

Microwave Magnetron



Magnetrons are well known and more utilized Vacuum Tube (VT) oscillators which generate High Power (HP) radiofrequency (RF) signals by transferring energy from an electron stream to a RF field. Electrons are emitted by a thermoelectric cathode, from which they are extracted by anode-cathode voltage. The electron trajectory is then deviated by the interaction with a static magnetic field in the axial direction, in order to let electrons oscillate between the anode resonant cavities, describing epicycloids. During this process, the electron velocity decreases, and with it, also its energy decreases since it is transferred to a RF oscillating field. Cavities represent a system of coupled oscillators with characteristic Normal Mode (NM) frequencies. NMs are called with their resonant electric field phase shift between two contiguous cavities [1].

Motivations

Multiphysics Simulation Ambient

Working conditions:

Thermal Expansion



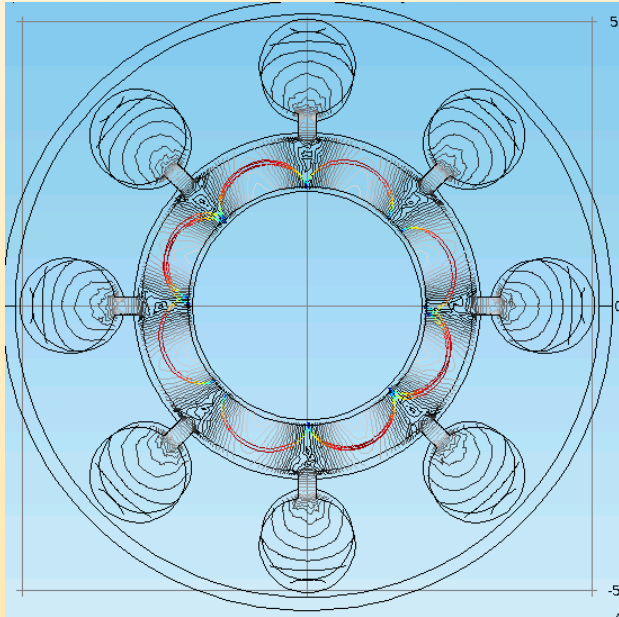
Mechanical Stresses

Electromagnetic
behavior

Cathode heating = Thermal expansion = Stress and displacement

The power dissipation of the cathode produces a considerable temperature increase and induces a thermal expansion of both the cathode and the anode and significant stresses and strains with consequent displacement of the resonant structure, which alter the desired Electromagnetic (EM). If the cavity temperature exceeds a certain threshold, oscillation failure or device damage may occur. Since device efficiency depends critically to the operating temperature, a Multiphysics (MP) approach has been adopted.

Proposed Magnetron Features



Operative frequency
 $f=9$ GHz

Normal Mode
 π -mode

Critical Field condition

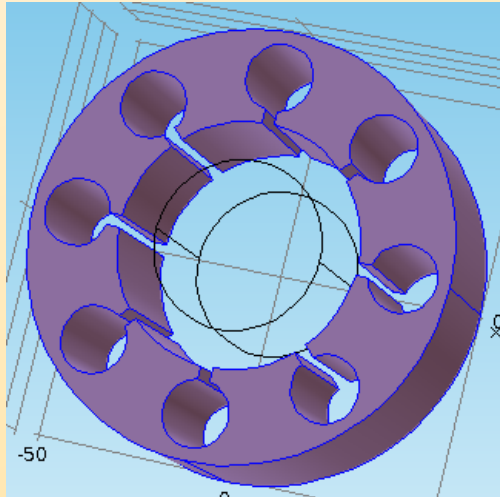
$$B_C = \sqrt{\frac{2mV}{ed^2}} \quad V_C = \frac{1}{2} \pi B r_m d f$$
$$r_m = (r_a^2 - r_k^2) / (2r_a),$$

In this study we describe an eight key holes X-Band Magnetron operating in π mode. By selecting opportune NM frequency, axial static magnetic induction B and anode cathode voltage V , electrons can oscillate and are not captured by the anode. This condition occurs in the critical field, in which the anode-cathode voltage must equal the critical voltage V_C and the axial magnetostatic induction must equal the critical induction B_C ; both related to the desired NM operative frequency f , which will correspond to the frequency of the generated microwave power [1].

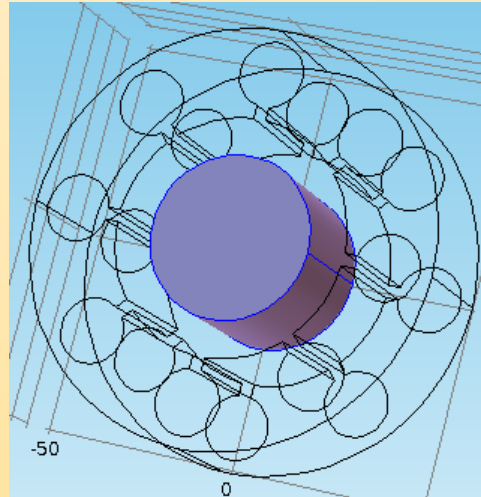
Proposed Magnetron Features

key holes Magnetron 3D Model - Materials

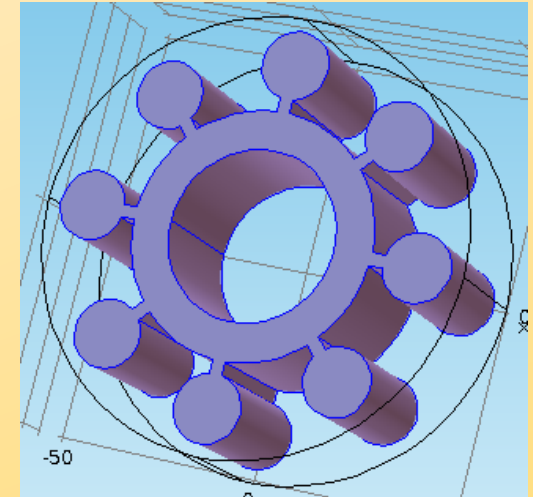
Copper Anode



Tungsten Cathode



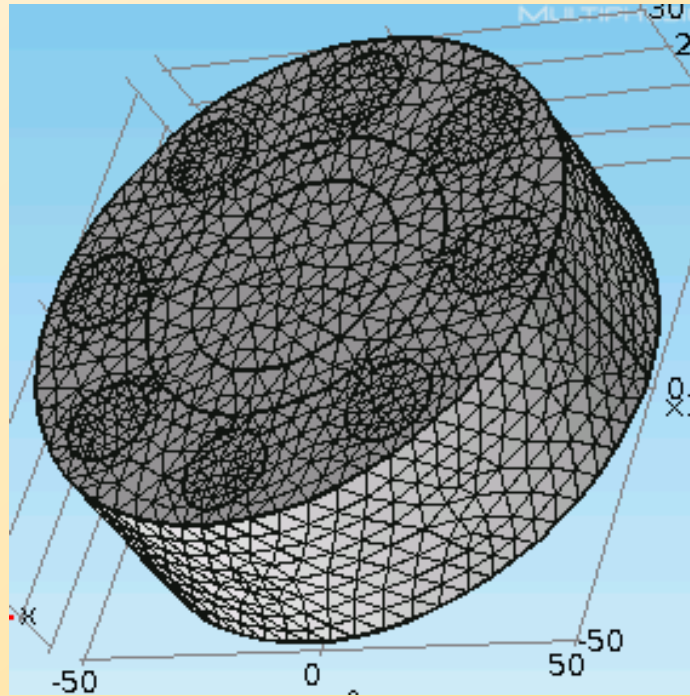
Non ideal Vacuum Interaction region



The proposed device is composed by a copper anode and tungsten cathode. In order to simplify the model, cathode surface is modeled as a copper layer. The comprised material between anode and cathode is a high vacuum medium that is air at pressure of $P = 10^{-10}$ bar. In order to ensure a great model reliability, all the materials are temperature dependent.

Proposed Magnetron Features

key holes Magnetron 3D Model - Mesh

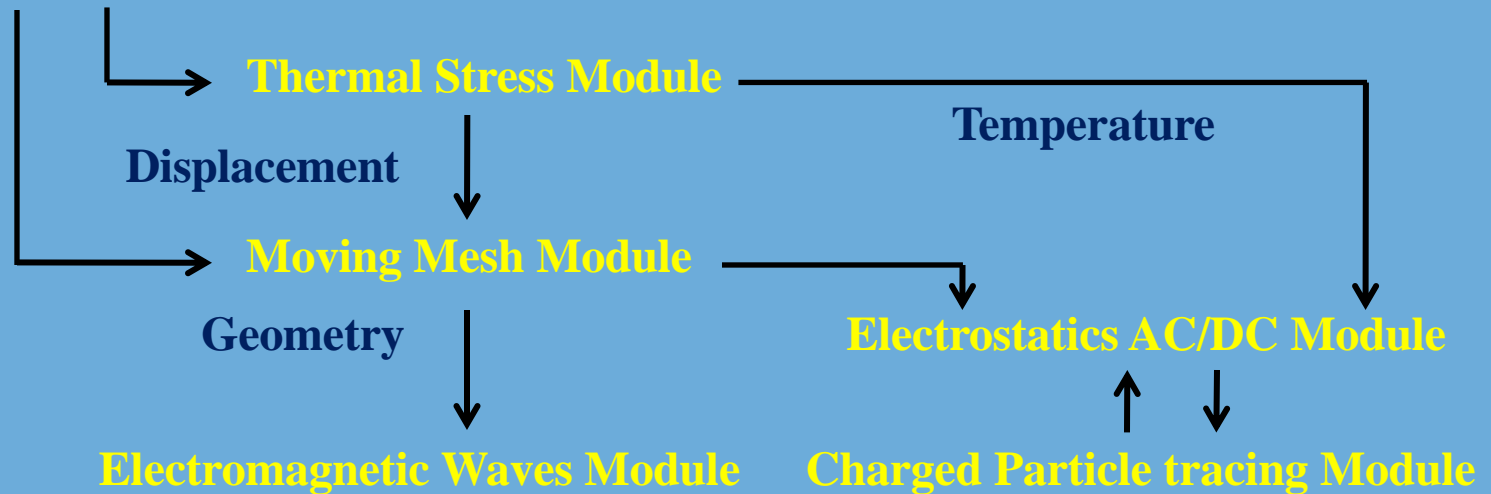


Due to the simplicity of the geometry, default settings have been adopted, by choosing Physic controlled mesh with Finer element size. Complete mesh consists of 45258 elements. Minimum element (mES) size is $4.08 \cdot 10^{-4}$ m, which corresponds to 0.012λ , where λ is the wavelength at 9 GHz.

Use of COMSOL Multiphysics

COMSOL Multiphysics Simulation Ambient

Electromagnetic behaviour and particles in EM field - Working conditions



COMSOL can couple TS, EM and PT analysis by employing Moving Mesh (MM) dedicated interface and storing temperature information. The TS module calculates temperatures and displacements [2]. The MM module moves the mesh in function of the displacement computed by the TS analysis [3]. TS and MM are employed in a single stationary analysis.

The EMW calculates the Eigen-frequencies with corresponding Resonant Electric fields [4], by performing an Eigen-value analysis on the new mesh and temperature. ES and CPT Modules calculate the Particle trajectories and related properties [5-6] by performing a time dependent analysis.

Use of COMSOL Multiphysics

COMSOL Multiphysics Simulation Ambient

Electromagnetic behaviour and particles in EM field - Working conditions

Thermal Stress Module

Displacement

Moving Mesh Module

Temperature

Geometry

Electrostatics AC/DC Module

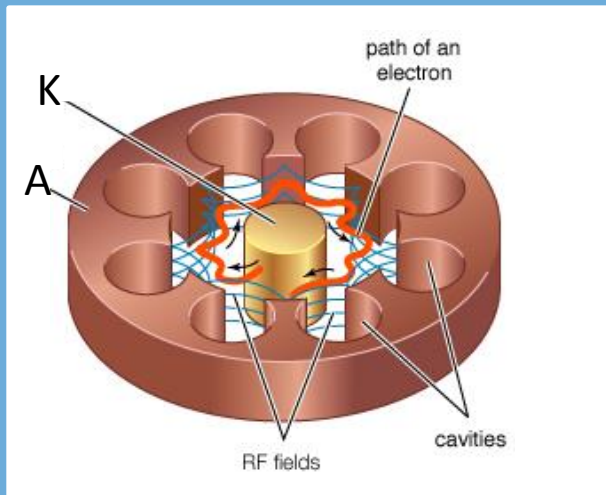
Electromagnetic Waves Module

Charged Particle tracing Module

Resonant Electric Field

Electron trajectories

Results post-processing



The superposition of the computed resonant field and the electron trajectories allows to individuate the correct operating Electrostatics and magnetostatic fields conditions, in order to defining the working points of the Magnetron.

Use of COMSOL Multiphysics

Thermal Stress Module

Temperature and displacement computation, applied to the entire structure

 Thermal Stress (ts)

 Thermal Linear Elastic 1


 Free 1

 Thermal Insulation 1

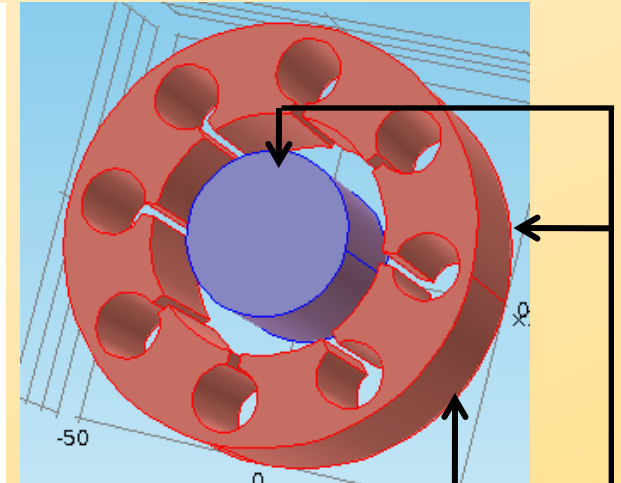
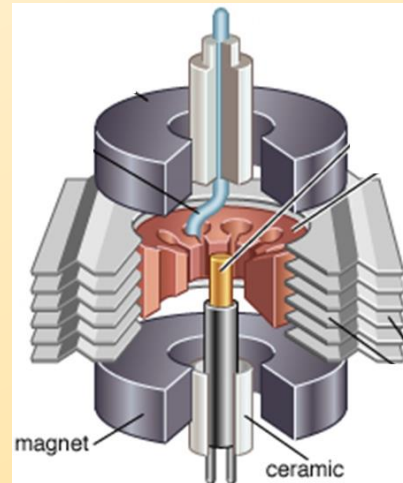
 Initial Values 1

 Heat Transfer in Fluids 1 → Non ideal vacuum

 Heat Source 1 → Thermoelectric Cathode $Q=8.7\text{GW}/\text{m}^3$

 Temperature 1 → External walls cooled by heat-sink system $T=35^\circ\text{C}$

 Fixed Constraint 1 → External surfaces locked to rigid supports



The non ideal vacuum atmosphere inside the Magnetron volume between anode and cathode is modeled only to describe the heat transfer from cathode to anode.

The cathode represents a constant volume heat sources. In order to reach the necessary temperature for thermo-electrical effect, $T=1050^\circ\text{C}$, the heat power density has been set to $Q = 0.405 [\text{GW}/\text{m}^3]$.

Use of COMSOL Multiphysics

Thermal Stress Module

Temperature and displacement computation, applied to the entire structure

Thermal Stress (ts)

Thermal Linear Elastic 1

Free 1

Thermal Insulation 1

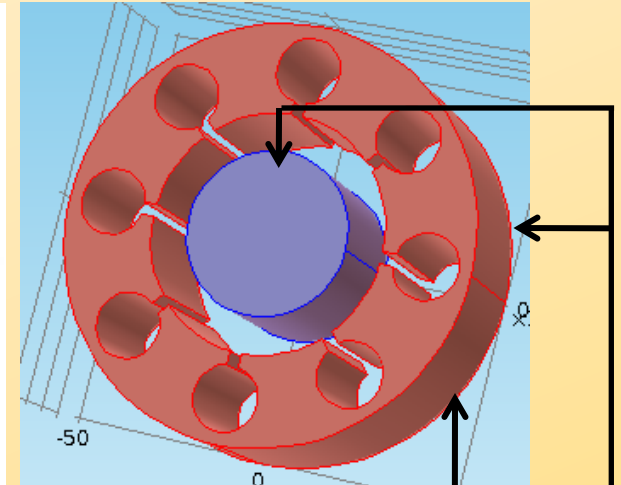
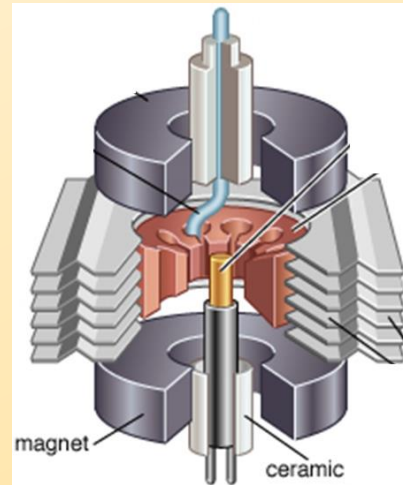
Initial Values 1

Heat Transfer in Fluids 1 → Non ideal vacuum

Heat Source 1 → Thermoelectric Cathode $Q=8.7\text{GW}/\text{m}^3$

Temperature 1 → External walls cooled by heat-sink system $T=35^\circ\text{C}$

Fixed Constraint 1 → External surfaces locked to rigid supports



The external lateral surfaces of the Magnetrons are cooled by heat-sink systems, typically set to 35°C . The external metallic surfaces of the anode and the basis surfaces of the cathode are locked to rigid structures in order to support the device. Thus they represent fixed constraints.

Use of COMSOL Multiphysics

Moving Mesh Module

Mesh displacement computation, applied to the entire structure

Moving Mesh (*ale*)

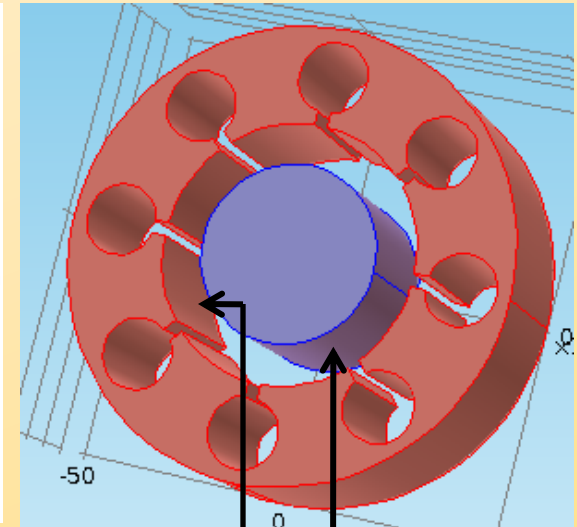
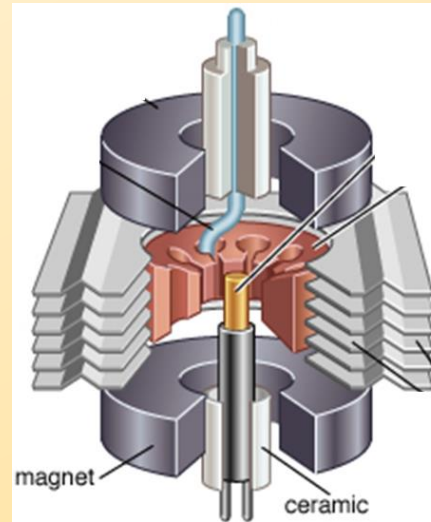
Fixed Mesh 1

Prescribed Mesh Displacement 1

Prescribed Deformation 1

Free Deformation 1

Prescribed Mesh Displacement 2



→ Anode and cathode

→ Non ideal vacuum

→ Anode and cathode surfaces adjacent to the non ideal vacuum volume

Anode and cathode represent the volumes subjected to structural formulation by TS analysis. The non ideal vacuum volume is free to move, since is subjected only to heat transfer in fluid formulation by the TS analysis [3].

Anode and cathode surfaces adjacent to the non ideal vacuum volume are deformed by the thermal stress computation.

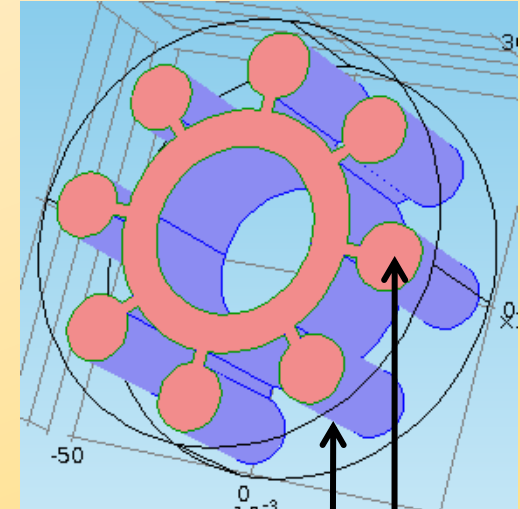
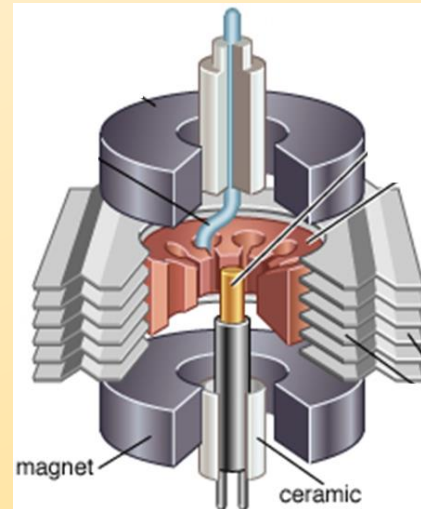
Use of COMSOL Multiphysics

Electromagnetic Waves Module

Eigen-frequencies calculation with corresponding resonant electric fields in the interaction region:
Applied only to the non ideal vacuum domain.

Electromagnetic Waves (*emw*)

- Wave Equation, Electric 1
- Perfect Electric Conductor 1
- Initial Values 1
- Impedance Boundary Condition 1
- Scattering Boundary Condition 1



→ Anode and cathode - internal (10mm)

→ Interaction region - base surfaces

The lateral cathode surfaces and the internal lateral anode surface are modeled in order to consider the losses due to the partial penetration of the electric field in the lossy material. The specified thickness of the anode and cathode boundaries is fixed to 10 mm. The surface bases of the interaction region are made of non ideal vacuum. So that, the plane wave which crosses this boundary must be free to feed forward [4].

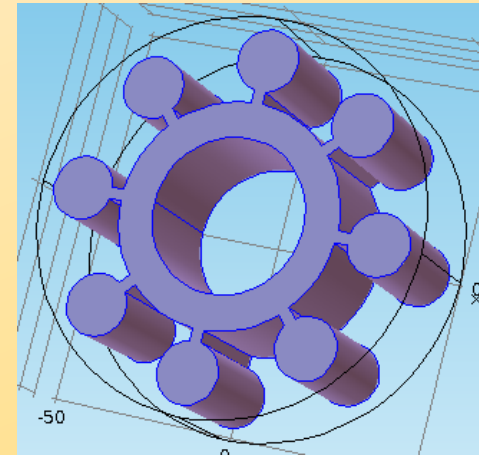
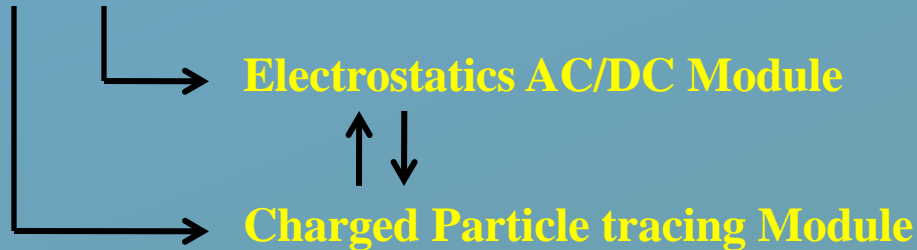
Use of COMSOL Multiphysics

Charged Particle in Electric field

Electrostatics field and particle trajectory calculation in the interaction region: Applied only to the non ideal vacuum domain.

COMSOL Multiphysics Simulation Ambient

Charged Particle in Electric field



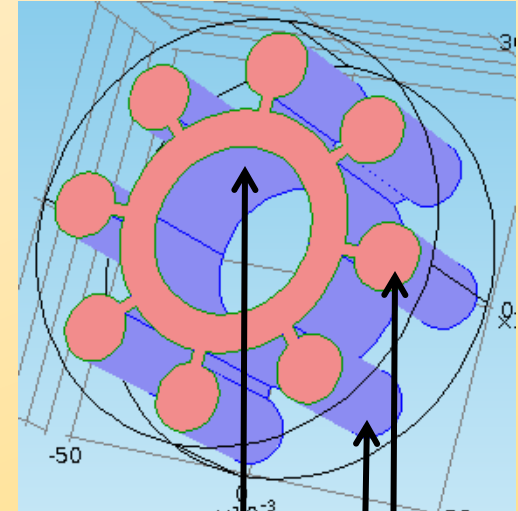
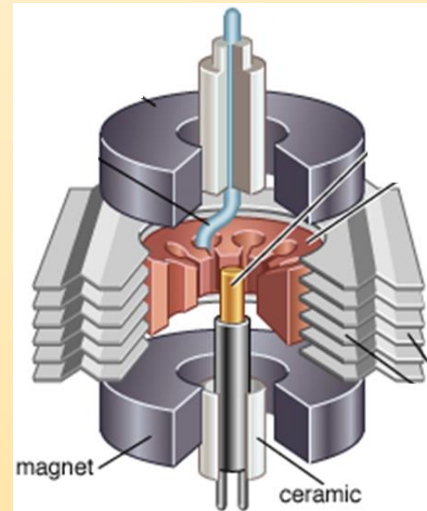
We have a two-way coupling between the particles and field: the field exerts a force on the particles and the particles exert a space charge on the field. So is necessary to solve the problem for the particles and fields simultaneously by couple a PT and an Electrostatics (ES) analysis [5].

Use of COMSOL Multiphysics

Electrostatics Module

Electrostatics field calculation in the interaction region: Applied only to the non ideal vacuum domain.

- * Electrostatics (es)
- Charge Conservation 1
- Zero Charge 1
- Initial Values 1
- Electric Potential 1
- Electric Potential 2
- Dielectric Shielding 1



→ Cathode $V = -60$ KV

→ Anode $V = 0$

→ Interaction region - base surfaces

The anode electric potential is set to zero and the cathode electric potential to $V_k = -60$ [MV]. Dielectric shielding is used to separate the anode electric potential to the cathode electric potential and is applied on the external boundary which connects anode and cathode [6]. The surface thickness has been set to 5.0 [mm].

Use of COMSOL Multiphysics

Charged Particle tracing Module

Particle trajectory calculation in the interaction region: Applied only to the non ideal vacuum domain.

Charged Particle Tracing (cpt)

Wall 1

Particle Properties 1

Inlet 1

Electric Force 1

Magnetic Force 1

Particle Field Interaction 1

Particle-Particle Interaction 1

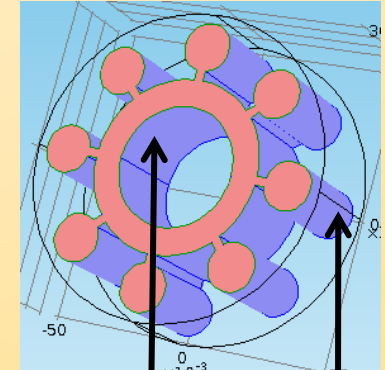
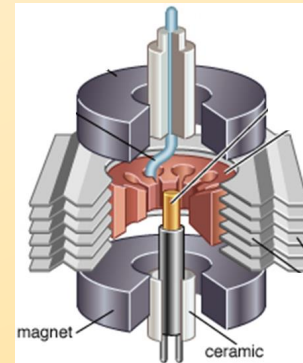
Cathode emitting surface

$F=q(-\nabla V)$ where V is calculated by ES Module

$F=q v \wedge B$ where B is the axial induction

Two way coupling: E field and space charge

Include interaction force to the total force



Electrons are released from the cathode boundary and accelerated by the Force $F=q(-\nabla V)$ where V is the anode cathode voltage calculated by ES Module. Electron trajectory is deflected by the Force $F=q v \wedge B$, where B is the design axial magnetic induction $B=1330$ G. Particle field interaction node adds the two-way coupling between the particle space charge and the electric field. Particle-Particle Interaction node includes the Coulomb interaction force between charged particles to the total force [5].

Use of COMSOL Multiphysics

Charged Particle tracing Module

Charge release discretization

Inlet 1

$$N = \frac{J s \Delta t}{e}$$



▼ Release Times

Release times:

range(1.8e-11,1.8e-11,5.4e-10)

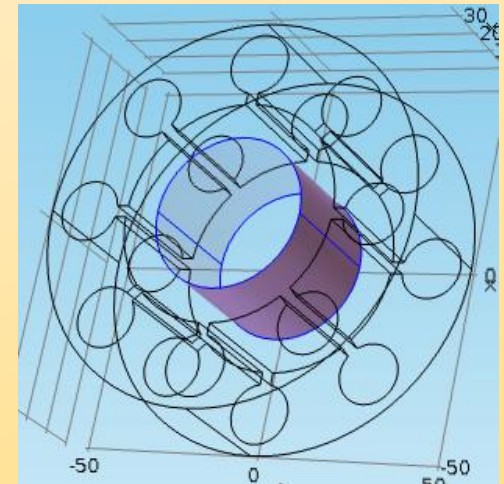
▼ Initial Position

Initial position:

Projected plane grid

Number of particles per release:

N 123

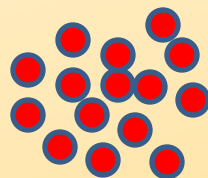
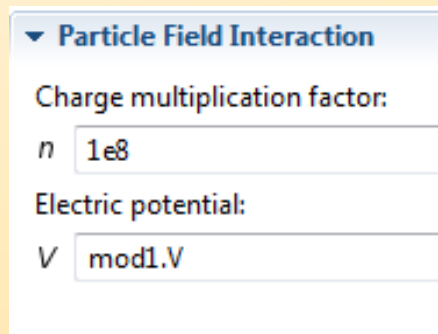


Since the cathode current density is constant in time and on the cathode surface, the charge release is represented by a short pulse sequence with initial null value of a defined number of particle per release N . Where I is the design cathode current, e the elementary charge of the electron and Δt is the time interval between two consecutive charge releases. For this design have been set $I = 110$ [A] and $\Delta t = 1.8 \cdot 10^{-11}$ [s], thus we have $N = 1.23 \cdot 10^{10}$ particles per release. In order to decrease computational costs, this number has been decreased to $N^1 = 123$. The particle release times have been set to start from $t = \Delta t$ and stop to $t = 30 \Delta t$, by steps of Δt .

Use of COMSOL Multiphysics

Charged Particle tracing Module

Particle field interaction and computational cost reduction



Chosen number of particle
per release $N^1=123$

Charge multiplication factor
 $n= N/N^1 = 10^8$

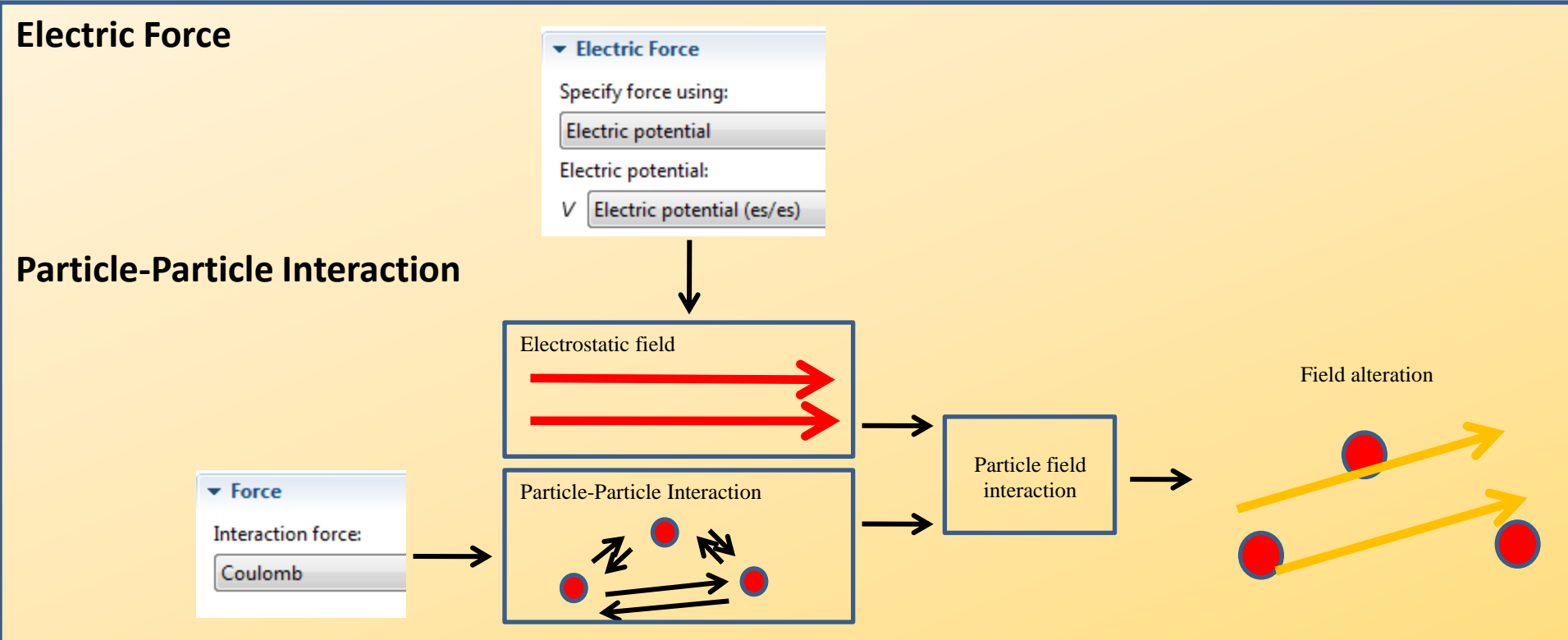


This feature adds two-way coupling between the particles and field, in order to model at the same time the space charge effect (exerted by the electrons on the ES field) and the force (exerted by the electric field on the charges).

In order to decrease computational cost, the number of particle pre release (in the Inlet feature) has been decreased to $N^1=123$ and a charge multiplication factor (in particle field interaction feature) $n = 10^8$ has been employed [5].

Use of COMSOL Multiphysics

Charged Particle tracing Module

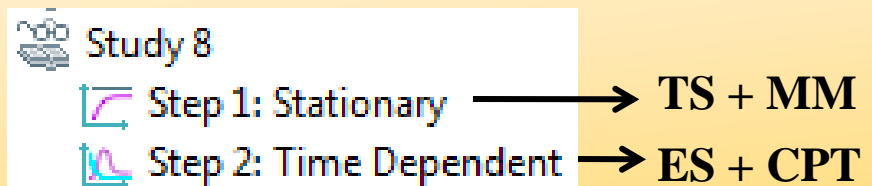
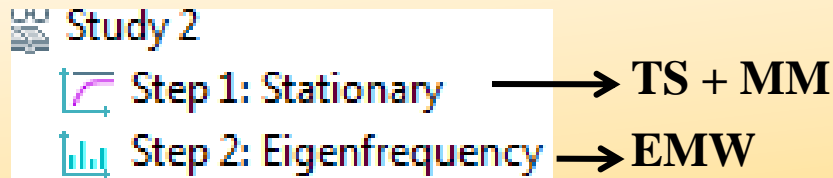
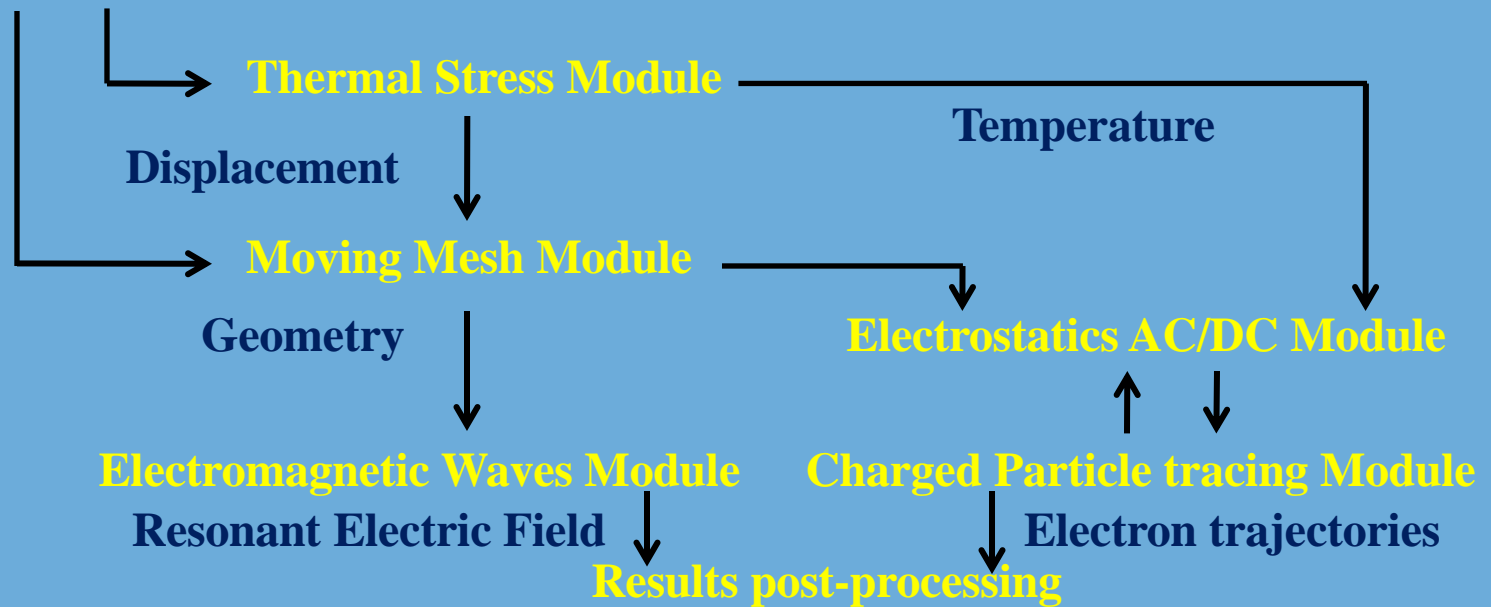


Particle-Particle Interaction feature is employed to include the Coulomb interaction force between charged particles to the total force. The particle position is step by step updated, and the process repeats until the specified end time for the simulation is reached [5].

Electric Force is employed to define the electric part of the Lorentz force $F=e(-\nabla V)$, specified via the electric potential computed time dependently by the ES module

Use of COMSOL Multiphysics

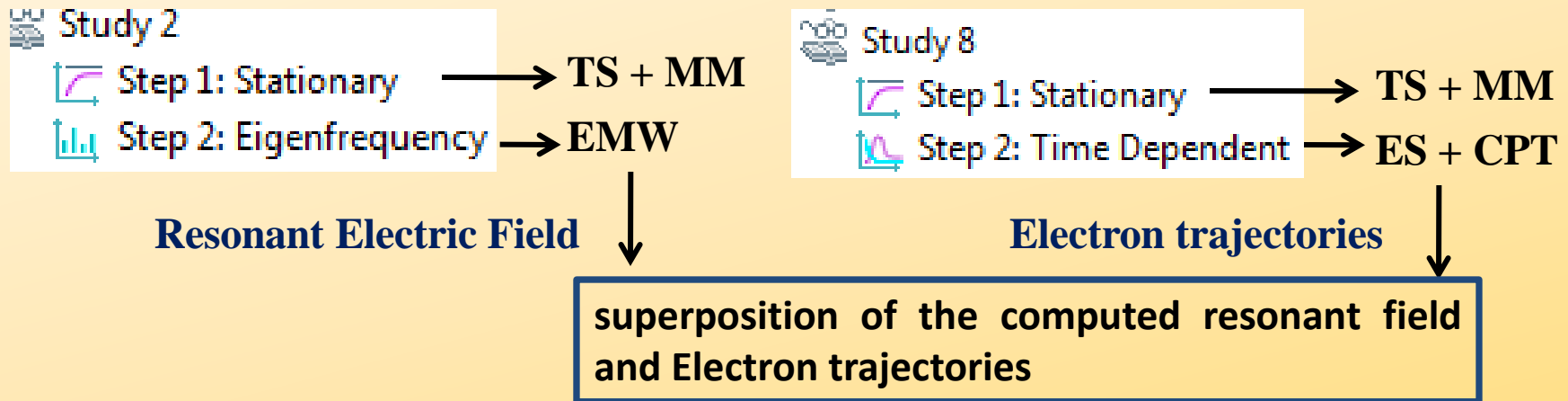
Electromagnetic behaviour and particles in EM field - Working conditions



The studies are organized in performing two steps: First, a stationary analysis to compute the thermal TS and MM, then a Eigenfrequency step to compute Resonant Electric Field and a time dependent step to compute electrostatic field and particle trajectories, which has been set to start at time $t=0$ and end at $t=120 \cdot \Delta t$, by steps of Δt

Use of COMSOL Multiphysics

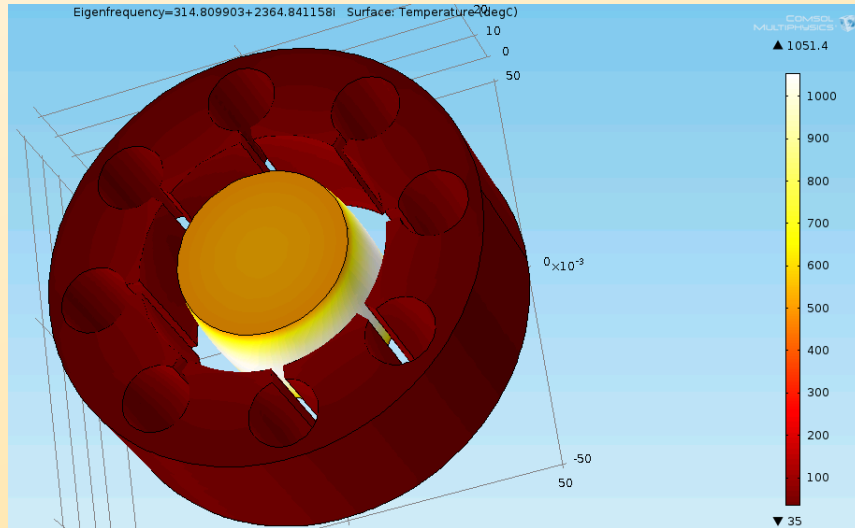
Results post-processing



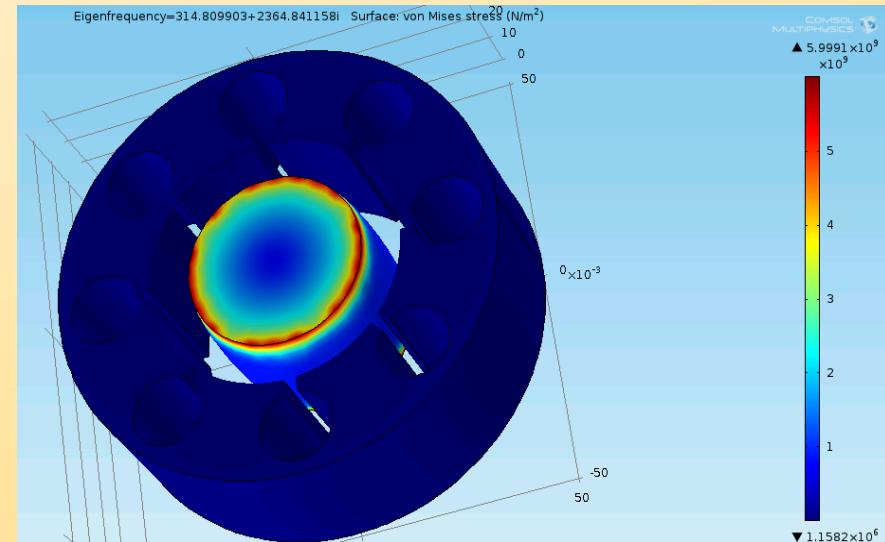
The superposition of the computed resonant field and the trajectories of the electron have been plotted on a plane which bisects the Magnetron structure. This study allows to individuate the correct operating electrostatic and magnetostatic fields conditions, , in order to defining the working points of the Magnetron.

Simulation Results

Temperature



Stress



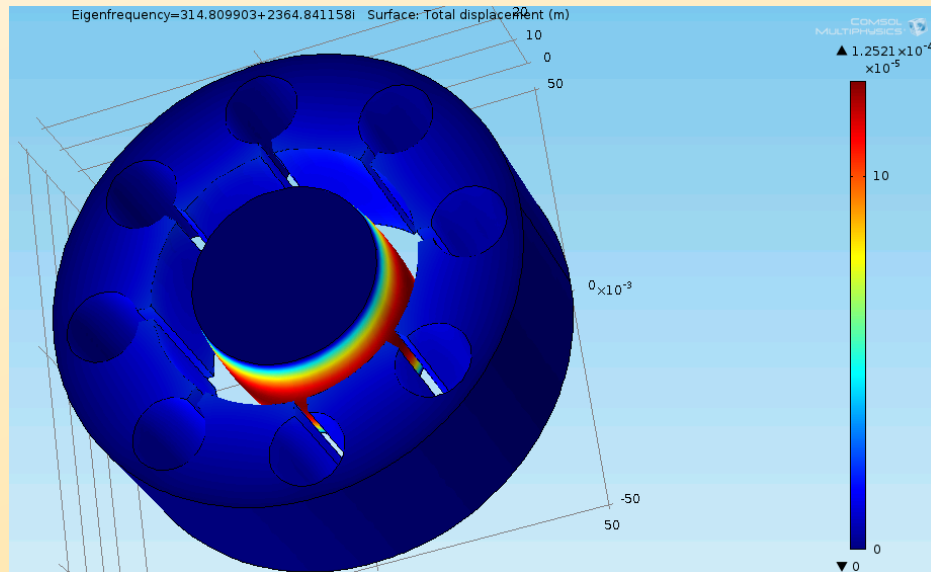
The deformation scale has been increased in order to better show the displacements. In the figures, black outlines represent the original conformation, and the stained volume represents the deformed structure.

By imposing a Heat density of $Q = 0.405$ [GW/m³], for the cathode heating, the TS stationary analysis has shown a maximum temperature of 1050°C on the cathode internal boundaries, perfectly according with the thermo-electrical threshold for cathode electron release.

The maximum stress is near the cathode base surfaces, since these ones are fixed constraints and cathode is the heat source. Maximum stress is about 6.0 [GN/m²].

Simulation Results

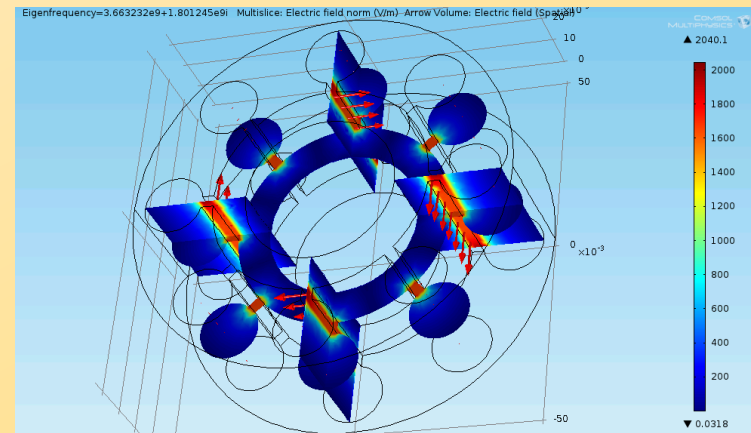
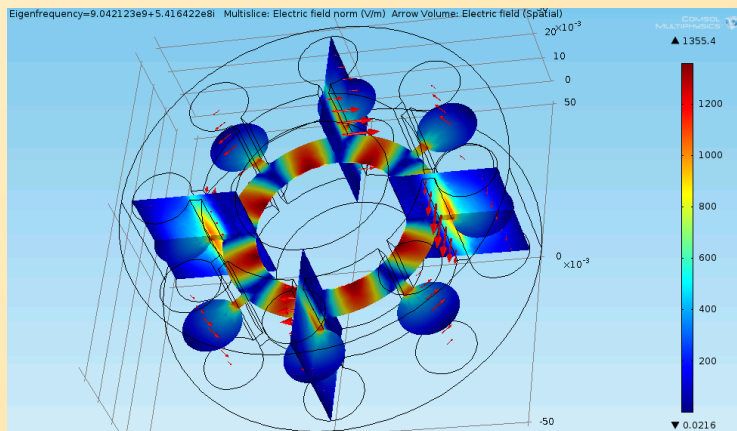
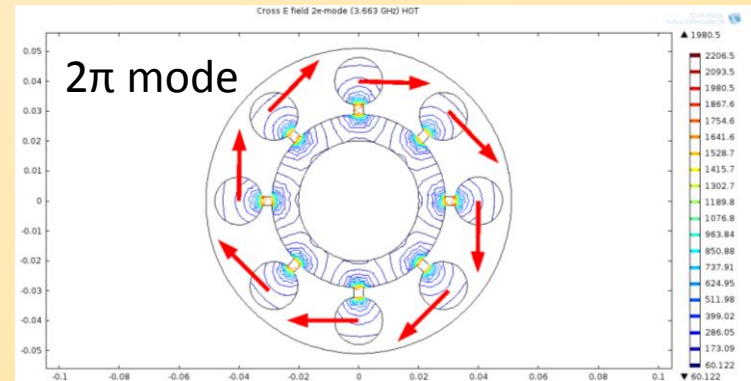
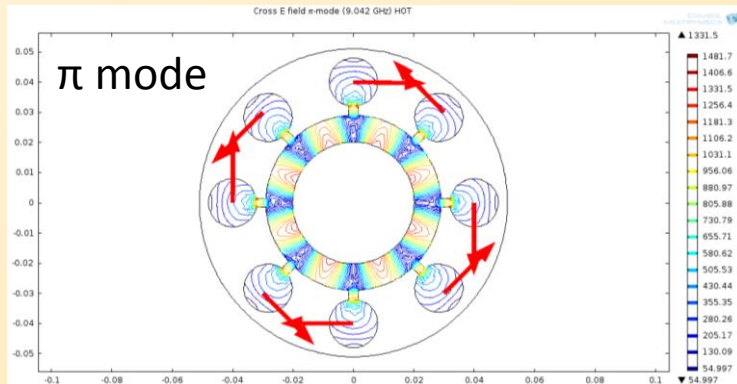
Displacement



The maximum total displacement is located on lateral cathode surface, and is about 0.125 [mm]. These values are very small respect the wavelength, so will result in producing a little alteration of the structure oscillating properties.

Simulation Results

Resonant Electric Fields in working condition



A cut plane has been set on the transversal section of the Magnetron and it has been used to visualize the Electric field streamlines, in order to evaluate the presence of the searched normal modes.

Simulation Results

Eigen-frequencies and Quality factors

	π mode	2π mode
Cold conditions	$f_{\pi} = 9.061$ GHz $Q_{\pi} = 8300.$	$f_{2\pi} = 3.673$ GHz $Q_{2\pi} = 1000$
Working conditions	$f_{\pi} = 9.042$ GHz $Q_{\pi} = 8250$	$f_{2\pi} = 3.663$ GHz $Q_{2\pi} = 950$

The resulting Magnetron EF's and Quality factors in cold conditions are:

$$f_{2\pi} = 3.673 \text{ GHz}, f_{\pi} = 9.061 \text{ GHz and } Q_{2\pi} = 1000, Q_{\pi} = 8300.$$

In Thermal-stress working conditions, the displacement and the electrical properties alteration of the materials cause a variation of the Eigen-frequencies to:

$$f_{2\pi} = 3.663 \text{ GHz}, f_{\pi} = 9.042 \text{ GHz}$$

and a variation of the quality factors to:

$$Q_{2\pi} = 950, Q_{\pi} = 8250.$$

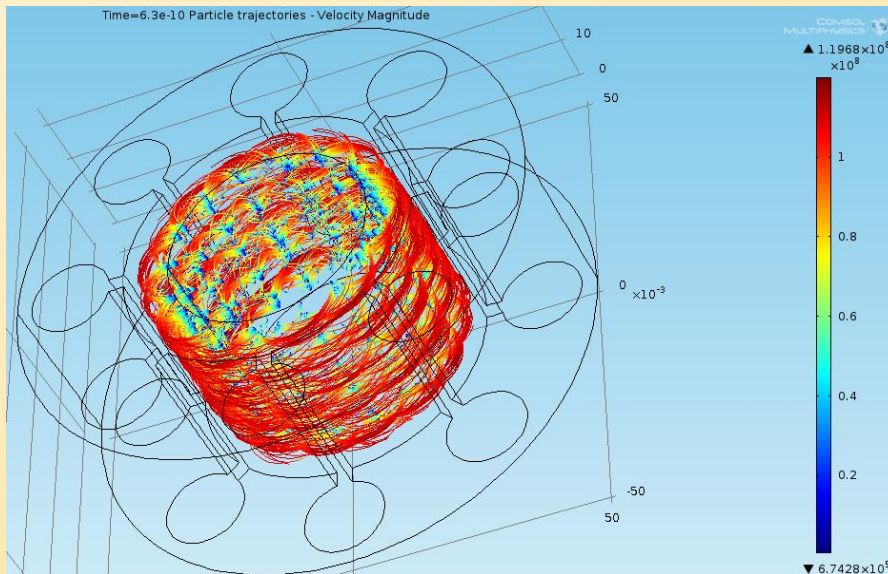
Simulation Results

Particle trajectories and velocities in π -mode

Cold conditions

$$v_{Max} = 1.196 \cdot 10^8 \text{ m/s}$$

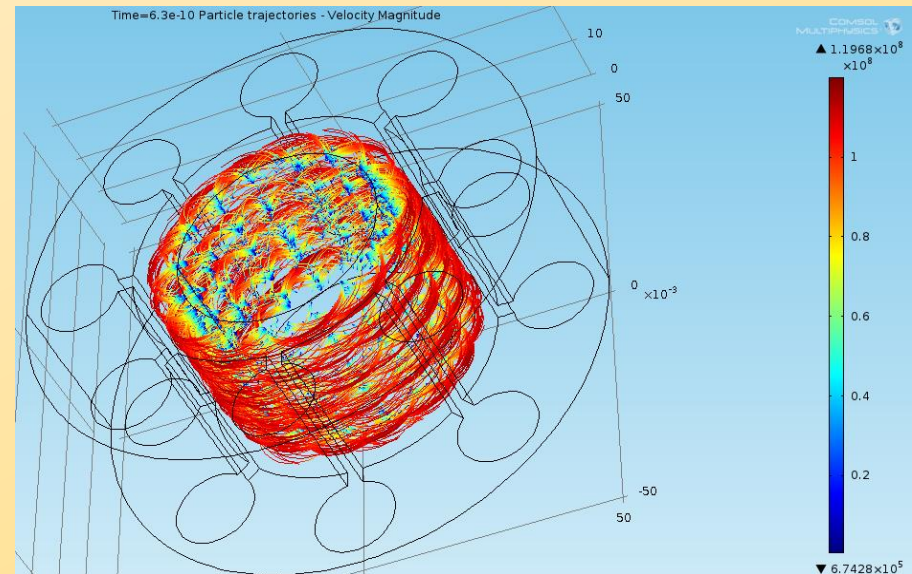
$$E_{Max} = 7.94 \text{ MV/m}$$



Working conditions

$$v_{Max} = 1.227 \cdot 10^8 \text{ m/s}$$

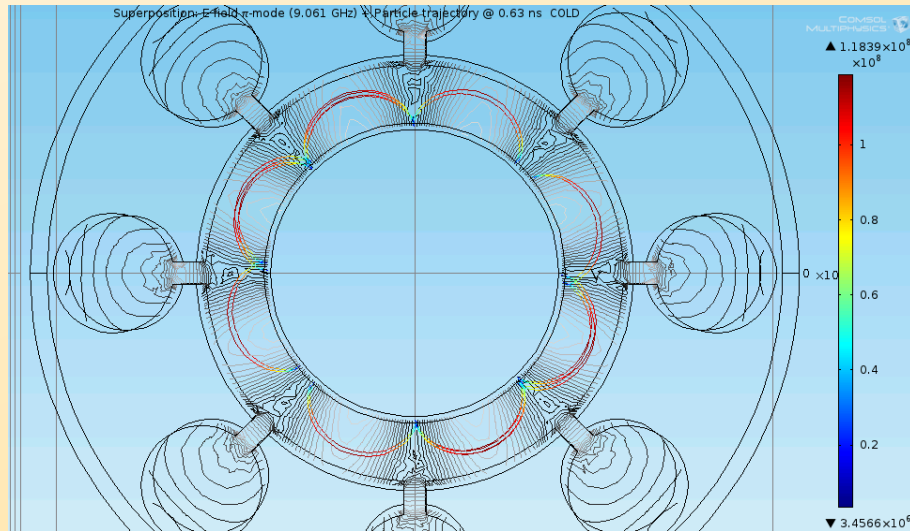
$$E_{Max} = 8.03 \text{ MV/m}$$



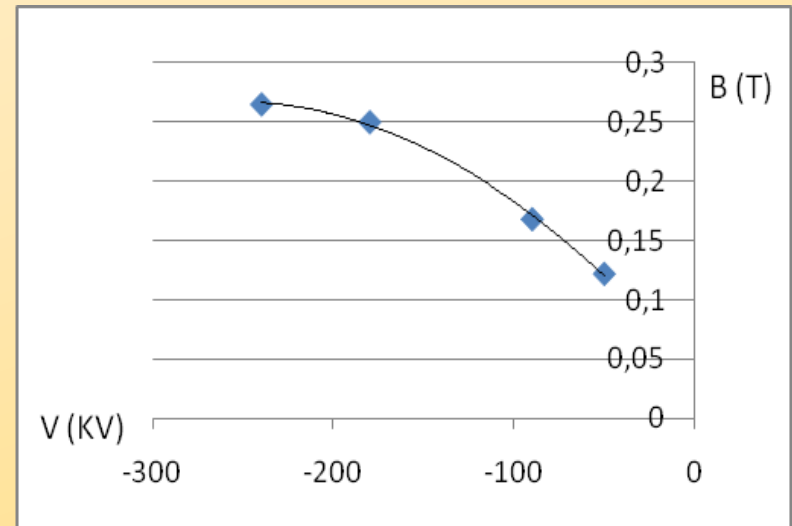
Thermal excitation contributes to increase the maximum particle velocity magnitude from $v_{Max-cold} = 1.196 \cdot 10^8$ [m/s] in cold conditions, to $v_{Max-hot} = 1.227 \cdot 10^8$ [m/s] in working conditions. Maximum electrostatic fields are: In cold conditions: $E_{max-cold} = 7.94$ [MV/m], and in thermal-stress working conditions: $E_{max-hot} = 8.03$ [MV/m].

Simulation Results

Superposition of particle trajectories and resonant field



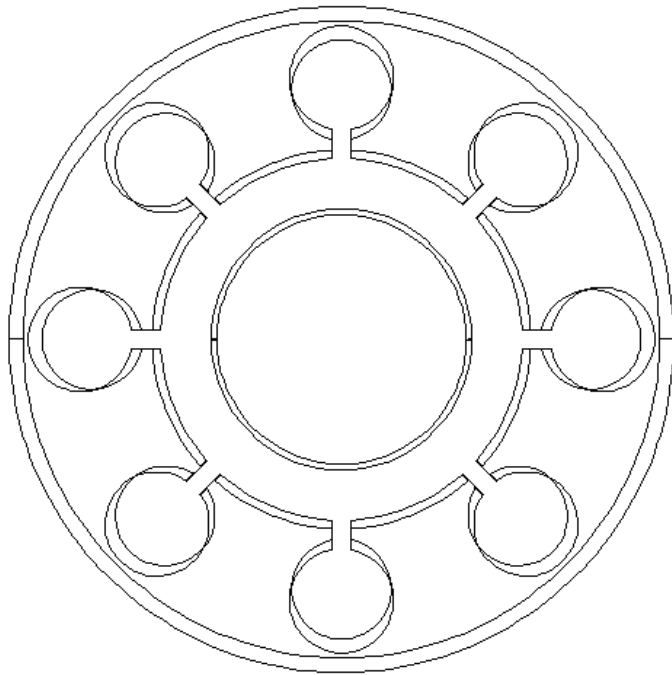
Magnetron Working Points - π mode



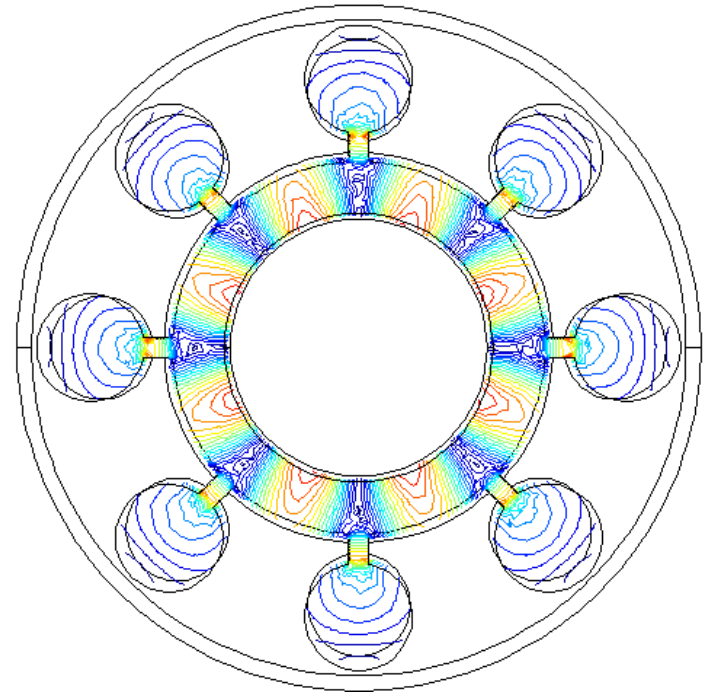
The superposition of the computed resonant field and the trajectories of the electron allows to individuate the correct operating electrostatic and magnetostatic fields conditions. By setting the static conditions of π mode operation and plotting particle trajectories, a superposition with π mode oscillating field shows a correct synchronism condition. The couples of electrostatic voltage V and magnetostatic induction B which ensures the superposition of particle trajectories with the resonant electric field are defined as Magnetron working points.

Simulation Results

Particle tracing animation



Particle motion from up to $t=2.16$ ns



Particle trajectories up to $t= 5.4 \cdot 10^{-11}$ s

First animation shows the particle motion from $t=0$ to $t=2.16$ ns.

Second animation shows the particle trajectories $t=0$ to $t= 5.4 \cdot 10^{-11}$ s.

Particles are released from $t=1.8 \cdot 10^{-11}$ s to $t= 5.4 \cdot 10^{-11}$ s, by steps of $\Delta t=1.8 \cdot 10^{-11}$ s.

Conclusions

- The Magnetron resonance and particle motion have been studied using COMSOL, at the same time with thermal expansion and mechanical stress. The resonance and velocity alteration due to thermal-structural effects has been documented.
- In order to decrease computational time and resources maintaining accuracy, the device model has been organized by using several strategies allowed by COMSOL.
- Expected results are been obtained and, according to this simulation, the Working Points of the proposed device have been found. By applying the design condition: $V=60\text{KV}$, $B=1330\text{G}$ in order to have $I=110\text{A}$; this device, with a typical efficiency of 40%, can produce a pulsed microwave peak power of 2.64 MW.

References

1. George B. Collins, *Microwave Magnetrons*, McGraw Hill, New York, 1948.
2. *COMSOL Structural Mechanics Module User's Guide* Version: May 2012 COMSOL 4.3.
3. *COMSOL Multiphysics User's Guide*; Version: 2010 COMSOL 4.3.
4. *COMSOL RF Module User's Guide* Version: May 2012 COMSOL 4.3.
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.