Design and Simulation of a 1.3 GHz Input Klystron Cavity

Robson K. B. e Silva
Nuclear and Energy Research Institute – IPEN
Av. Prof. Lineu Prestes, 2242 – São Paulo, SP, Brazil
rkeller@usp.br

Cláudio C. Motta
University of Sao Paulo
Av. Prof. Lineu Prestes, 2468 – São Paulo, SP, Brazil
ccmotta@usp.br

Abstract—**This paper presents a sequence of steps to begin the project of a cylindrical reentrant klystron cavity for 1.3 GHz. One analytical method and different CAD tools such as SUPERFISH and 3D eigenmode solver have been used for designing the cavity. The external coupling problem of the cavity is also discussed and is proposed a technique to get the critical coupling.**

Keywords - Klystron, reentrant cavity, CST Microwave Studio, SUPERFISH, HFSS, AJDISK.

I. INTRODUCTION

A klystron amplifier is an electronic device that amplifies microwave signals, based on the principle of velocity modulation, consisting of: an electron gun to provide the beam, a RF section that consists of a series of reentrant cavities connected together with hollow metallic pipe called drift tube and, at the end, a collector to dump the spent beam. In the drift tube region the electron beam interacts with the input RF signal to be amplified.

The operation of a klystron can be described in terms of the electron bunching and using only two cavities. The first cavity is excited by the input signal and it acts as the buncher and velocity-modulates the beam. After the velocity modulation, there are two groups: fast electrons and slow electrons. In the drift tube, as the fast electrons are modulated by last, these electrons reach the slow ones. As consequence, the density increases until forming one bunch (electron bunch) that has a high current associated with it. Putting a cavity where the electron bunch takes place it is possible to extract the amplified signal (output cavity). On the one hand, the RF section design plays a vital role in deciding the tube performance parameters like gain, bandwidth and the overall efficiency [1]. On the other hand, the cavity R_{sh}/Q_0 is one of the most important parameter to be determined in the design of a klystron amplifier. In this problem, the gain of a klystron is proportional to the cavity shunt resistance R_{sh} that describes the ability of the cavity in doing work on the electron beam, and the bandwidth proportional to the cavity $1/Q_0$, where Q_0 specifies the frequency selectivity and performance, in general, of a resonant circuit. Then, R_{sh}/Q_0 is a useful figure of merit in describing the effect of the each cavity on the gain-bandwidth product of overall amplifier.

This paper is organized as follows. Section II presents the cavity design. Initially, in order to begin the project, a mathcad model is used to obtain the set of cavity parameters for a desired frequency and a negligible reentrance. Afterwards, a Superfish model (2D software) is used to design, from the mathcad model, a reentrant cylindrical cavity. Then, the resulting cavity is simulated using two 3D eigenmode solver and the results are compared. Besides, the input cavity coupling is discussed. Finally, the conclusion is presented in Section III.

II. CAVITY DESIGN

The cavities used in a round beam klystron are of cylindrical reentrant type such as shown in Fig. 1.

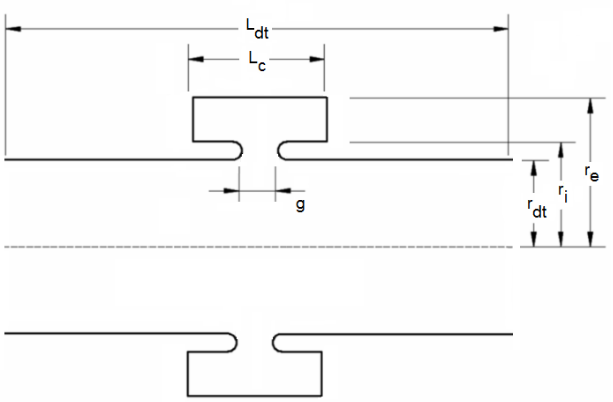

Fig. 1. Geometry of a reentrant cylindrical klystron cavity and drift tube used in this article .

The design parameters of the cavity are: cavity height L_c, drift tube radius r_{dt}, gap g between two drift tubes inside the cavity, external radius r_e , and internal radius r_i. The length of the drift tube is L_{dt}.

Initial design of the cavity has been done by analytical formula for frequency 1.3 GHz. Then the simulation has been carried out using SUPERFISH, for design optimization and later the simulation has been done by two 3D eigenmode solver software.

A. *The Mathcad Model*

An accurate calculation of the parameters that characterize the reentrant cavities is fundamental in microwave vacuum electronics devices design, such as klystron amplifiers. But, in order to begin the project, the admittance matching technique

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of the gap of interaction between the cavity and the drift tube, presented by Kowalczyk to calculate the loading of a resonant cavity by an electron beam [2] is used to find the dispersion relation that allow to calculate the frequencies supported by an unloaded, perfect conducting reentrant cylindrical cavity, as can be seen in the Fig. 2. The admittance matching technique for this problem is to achieve a solution to the electromagnetic fields supported by the cavity. The knowledge of the solution of the fields for both regions and in order that the admittance of the gap should be the same regardless of the representation of the fields, it is obtained a dispersion equation that allows the solution of the problem [3].

In this article, for a desired frequency, it is obtained the set of cavity parameters: cavity height L_c, drift tube radius r_{dt}, gap g, external radius r_e, and the lenght of the drift tube is L_{dt}.

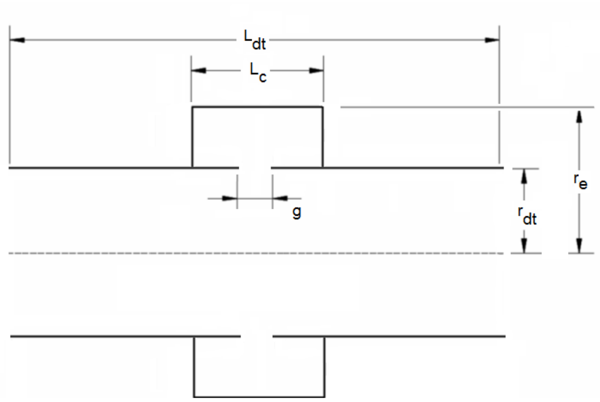

Fig. 2. Geometry of a klystron cavity and drift tube used in the mathcad model.

Then, for the frequency of 1.3 GHz, Table I presents the the set of cavity parameters.

TABLE I. CAVITY PARAMETERS USING THE MATHCAD DISPERSION EQUATION FOR FREQUENCY OF 1.3 GHZ.

Quantity	***Value***
Cavity length L_c, *mm*	47.50
External cavity radius r_e, *mm*	50.00
Gap g, *mm*	5.00
Drift tube radius r_{dt}, *mm*	14.00
Lenght of the drift tube L_{dt}, *mm*	120.00

B. The Superfish Model

Using the parameters of the Table I as the starting point to SUPERFISH [4], and considering the reentrance so small as possible, Fig. 3 shows the distribution of the electric field inside the klystron cavity (Fig. 2).

The frequency, in this case, is 1.323 GHz. In order to decrease the value of the frequency, the cavity parameters were modified and the final result is shown in Table II.

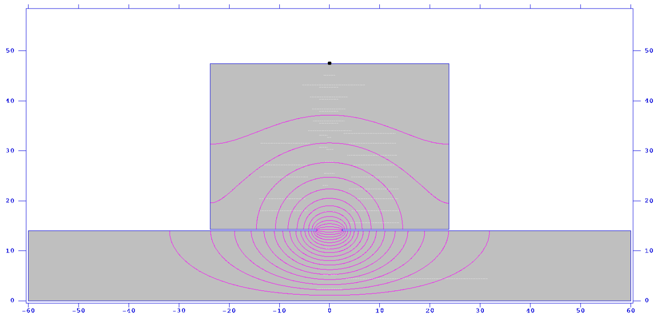

Fig. 3. Cross section of the electric field considering the cavity of the Fig. 2 with dimensions shown in Table I, and using SUPERFISH.

TABLE II. CAVITY PARAMETERS USING THE SUPERFISH SOFTWARE FOR FREQUENCY OF 1.3 GHZ.

Quantity	***Value***
Cavity length L_c, *mm*	45.00
External cavity radius r_e, *mm*	44.50
Internal cavity radius r_i, *mm*	18.00
Gap g, *mm*	5.00
Drift tube radius r_{dt}, *mm*	14.00
Lenght of the drift tube L_{dt}, *mm*	120.00

Fig. 4 shows the distribution of the electric field inside the klystron cavity, with dimensions according to Tab. II.

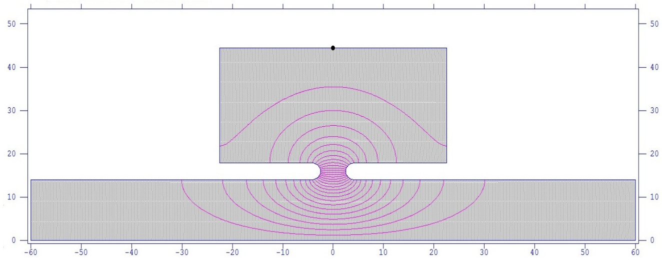

Fig. 4. Cross section of the electric field considering the cavity of the Fig. 1 with dimensions shown in Table II, and using SUPERFISH.

A parameter of great importance in studies of resonant cavities is the ratio of the effective resistance of the cavity (shunt resistence), given by

$$R = \frac{\left[\int_{axis} \vec{E} \cdot d\vec{l} \right]^2}{2P_L}, \tag{1}$$

and the quality factor Q, given by

$$Q = \frac{\omega W}{P_L}, \tag{2}$$

where ω is the angular frequency, W denotes the total energy stored in the cavity and P_L is the power loss on the cavity walls [5]. Combining (1) and (2), one has

$$\frac{R}{Q} = \frac{\left[\int_{axis} E_z(z)\,dz \right]^2}{2\omega W}. \tag{3}$$

The value for W can be taken from the (.SFO) file. The TABLPLOT (.TBL) file generated by SUPERFISH simulation gives the axial and radial electric field distribution in the cavity axis. The fields are shown in Fig. 5. Then, the voltage V is given by the line integral of the axial electric field along the axis.

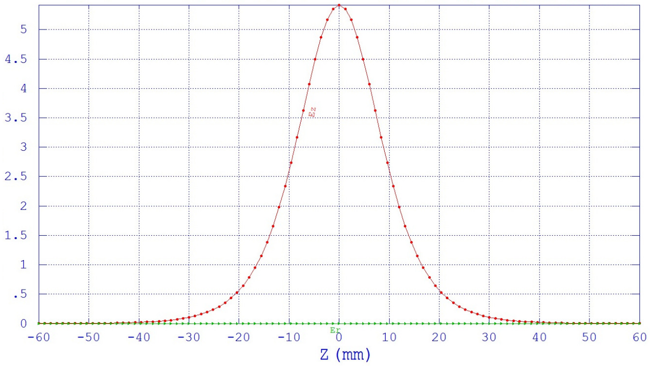

Fig. 5. Distribution of the axial and radial electric field along the z axis.

Table III presents the main parameters of the cavity.

TABLE III. PARAMETERS OF THE CYLINDRICAL CAVITY CALCULATED USING SUPERFISH.

Quantity	***Values***
Frequency f , GHz	1.291
Cavity R_{sh}/Q_0, Ω	71.87
Unloaded quality factor Q_0	8592

C. The 3D Eigenmode Solver 1

The optimized dimensions from SUPERFISH are taken as input for two 3D eigenmode solver software [6] to verify the frequency and R_{sh}/Q_0.

The cavity (Fig. 1) has been re-simulated in 3D using the eigenmode solver 1 as shown in Fig. 6.

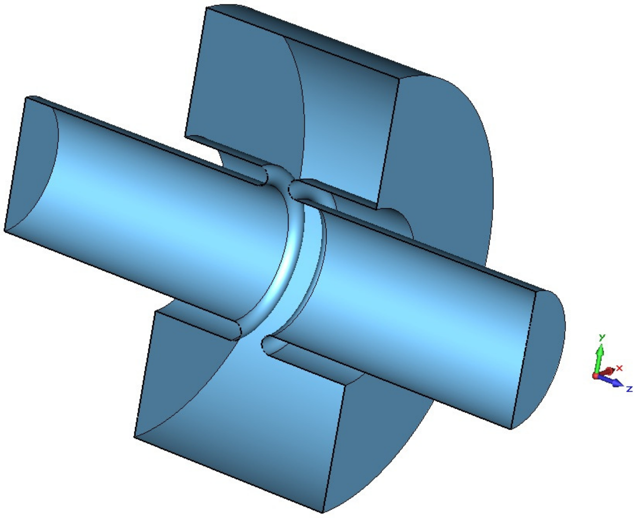

Fig. 6. Cross section of the 3D reentrant cylindrical klystron cavity and drift tube designed using the eigensolver 1.

The corresponding frequency is found to be 1.300 GHz, which is close to the SUPERFISH results. The axial electric field distribution in the cavity axis is shown in Fig. 7. The R_{sh}/Q_0 value has also been calculated using the eigenmode solver 1.

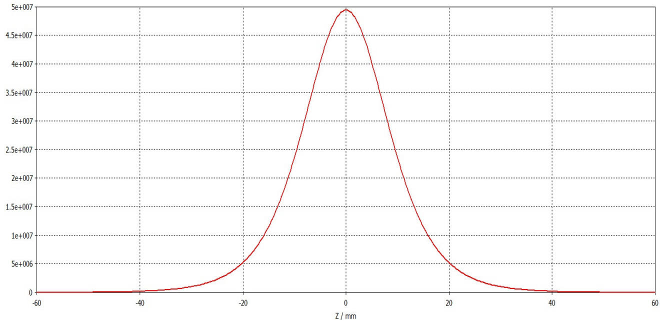

Fig. 7. Distribution of the axial electric field along the z axis.

The comparison of the results from SUPERFISH and 3D eigenmode solver are given in Table IV.

TABLE IV. COMPARISON BETWEEN THE PARAMETERS OF THE CYLINDRICAL CAVITY CALCULATED USING SUPERFISH AND EIGENSOLVER 1.

Quantity	***Values***	
	Superfish	***3D eigensolver 1***
Frequency f , GHz	1.291	1.300
Cavity R_{sh}/Q_0, Ω	71.87	73.43
Unloaded quality factor Q_0	8592	9908

D. The 3D Eigenmode Solver 2

The optimized dimensions from SUPERFISH are taken again as input for the second 3D eigenmode solver [7] to verify the frequency and R_{sh}/Q_0.

The cavity (Fig. 1) has been re-simulated in 3D using the eigenmode solver 2 as shown in Fig. 8.

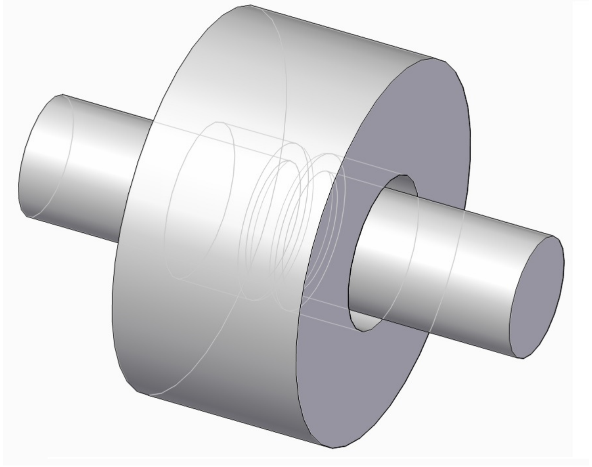

Fig. 8. 3D reentrant cylindrical klystron cavity and drift tube designed using using the eigenmode solver 2.

The corresponding frequency is found to be 1.302 GHz, which is close to the SUPERFISH and the eigensolver 1 results. The axial electric field distribution in the cavity axis is shown in Fig. 9. The R_{sh}/Q_0 value has also been calculated using the eigensolver 2. The comparison of the results from SUPERFISH and the two 3D eigenmode solver are given in Table V.

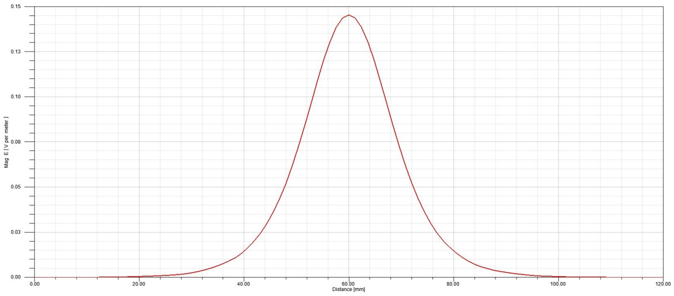

Fig. 9. Distribution of the axial electric field along the z axis.

TABLE V. COMPARISON BETWEEN THE PARAMETERS OF THE CYLINDRICAL CAVITY CALCULATED USING SUPERFISH AND TWO 3D EIGENMODE SOLVERS.

Quantity	***Values***		
	Superfish	***3D eigensolver 1***	***3D eigensolver 2***
Frequency f , GHz	1.291	1.300	1.302
Cavity R_{sh}/Q_0, Ω	71.87	73.43	72.40
Unloaded quality factor Q_0	8592	9908	8475

The deviation between the simulated values of R_{sh}/Q_0 is around 2%, which demonstrates that both software are very effective in simulating R_{sh}/Q_0.

With respect of Q, the deviation between Superfish and 3D eigensolver 2 values is around 1.4%, which demonstrates good agreement, but the deviation between Superfish and 3D eigensolver 1 or between both 3D eigensolvers is more than 15%. Then, in these cases more simulations are required because was not verified good agreement between the simulated values of Q.

Another result of great relevance is the R_{sh}/Q_0 variation with the gap width variation. But, changing the gap width the frequency changes as well. Then, it is necessary to change the external cavity radius in order to keep the frequency unchanging (1.3 GHz). Fig. 10 shows the R_{sh}/Q_0 variation with the gap width variation. It shows the external cavity radius variation as well.

E. Input cavity coupling

Beside the design of klystron cavity, a more relevant problem is that concerning with the input coupling. In order to modulate the electron beam velocity in cavity gap it is necessary to connect the cavity with an external RF power supply. The net effect of this coupling is external loading of the cavity implying in a shift frequency or namely external detuning. The 3D eigenmode solver 1 was also used to carry out this problem.

In this way the loaded cavity quality factor Q_L writes

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_e}, \tag{4}$$

where Q_e is the external quality factor. The coupling coefficient is defined as

$$\beta = \frac{Q_0}{Q_e}. \tag{5}$$

When $\beta = 1$ the coupling is named to be critical and the maximum transfer of energy between the external RF supply and the cavity takes place.

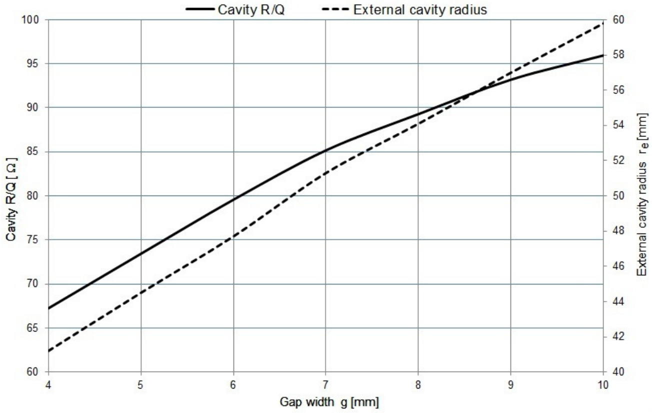

Fig. 10. R/Q and external cavity radius variation with the gap width variation. The frequency is 1.3 GHz.

Figure 11 shows the input cavity with 50 Ω coaxial coupling, the antenna loop and the lossy material post.

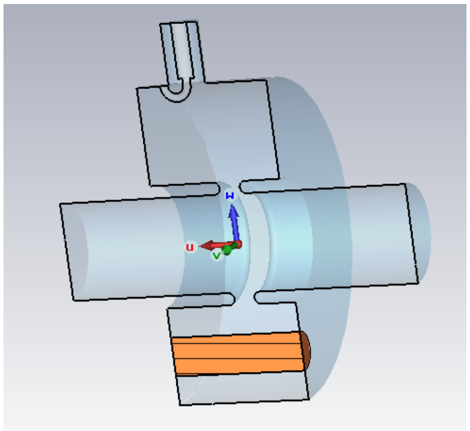

Fig. 11. Input cavity with external coupling, antenna loop and the post absorber.

The position of the coaxial coupling, antenna loop deepness, gap length, cavity offset, and electric conductivity of the lossy material (FeCr alloy) were all varied to get a critical coupling. It is verified the conductivity of lossy material and the antenna loop deepness were the parameters with the most effectiveness to solve the external frequency detuning problem. Table VI shows the found parameters for $\beta \sim 1$. The cavity dimensions were also adjusted due to external frequency detuning.

TABLE VI. INPUT CAVITY PARAMETERS FOR THE CRITICAL COUPLING.

Quantity	***Value***
Cavity length L_c , *mm*	45.00
External cavity radius r_e , *mm*	55.00
Internal cavity radius r_i , *mm*	22.00
Cavity conductivity (copper), *S/m*	5.8×10^6
Cavity Gap g , *mm*	7.00
Gap blend, *mm*	2.00
Gap offset, *mm*	2.00
Drift tube radius r_{dt} , *mm*	18.00
Drift tube length L_{dt} , *mm*	120.00
External diameter of coaxial input, *mm*	12.70
Internal diameter of coaxial input, *mm*	5.52
Coaxial input height, *mm*	20.00
Loop antenna radius, *mm*	4.00
Loop antenna thickness, *mm*	2.70
Loop antenna deepness, *mm*	1.40
Post diameter, *mm*	12.00
Post offset from the axis, *mm*	36.00
Lossy material electric conductivity, *S/m*	7.4×10^5
External cavity quality factor Q_e	3440
Unloaded cavity quality factor Q_0	3492
Coupling factor β	1.02
Loaded cavity quality factor Q_L	1733
Loaded cavity frequency, f_L, GHz	1.308

III. CONCLUSION

In this work the design of a reentrant cylindrical cavity for a 1.3 GHz input klystron amplifier with an external coupling was presented. It has been done using different CAD tools and the results are mostly in mutual agreement.

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