Design and Analysis of RF Section and Beam Wave Interaction for C Band 250 kW CW High Power Klystron

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Abstract Klystron is vacuum electron device operating in microwave range of frequencies. It is used as power amplifier in a variety of systems including radars, particle accelerators and thermonuclear reactors. A precise simulation of beam wave interaction in klystron is useful not only to understand its operation but also in development of tube with minimum iterations in fabrication. In the present case standard design codes like POISSON'S SUPERFISH, AJDISK and MAGIC 2D have been used to estimate and optimize different design parameters of klystron for desired tube performance. The paper presents the results of RF-section simulation of 250 kW CW C-band klystron with specifications as given in Table 1.

Keywords Reentrant Cavity, Beam Wave Interaction, Klystron

A 250 kW CW C-Band klystron with specifications as given in Table 1 is under development at CEERI, Pilani (India). It is to be used as a RF source in ITER program.

Table 1. Specifications of 5GHz klystron

Parameters	Specification
Operating frequency	5 GHz
Output power	250 kW
Beam voltage	60 kV
Beam current	10 A
No. of cavities	6
Efficiency	>40%
Gain	>40dB

1. Introduction

RF section has been designed for interaction between electron beam from electron gun and modulating signal coming from input cavity of the klystron. The RF-section consists of two main parts:

Resonant Cavities

The input and the output are taken from the tube via the resonant cavities. The exchange of energy between accelerated electron beam and RF signal takes place at the gap of cavity.

Drift Tubes

The RF interaction structure essentially consists of a series of reentrant cavity resonators connected together with metallic pipes called drift tubes. Drift tube is the space between two successive cavities. In the drift length the electrons group into bunches after undergoing a change in velocity while passing through the cavity gap.

2. Theory, Simulation, Results and Discussions

Poisson's Superfish is a collection of programs for calculating static magnetic and electric fields and radio-frequency electromagnetic fields in either 2-D Cartesian coordinates or axially symmetric cylindrical coordinates. The programs generate a triangular mesh fitted to the boundaries of different materials in the problem geometry. Plotting programs and other postprocessor codes present the results in various forms. The design of individual Cavities and calculation of their respective R/Q is done in Poisson's Superfish. RF cavity of 5GHz is designed by varying its radius to optimized resonant frequency and R/Q value of input and output cavities. Drift tube nose angle variation optimized to find correct value of cavity R/Q.

A. Design Results Using Poisson's Superfish

Case I: Tapering angle (θ) = 60°

 Figure 1. Electric field profile at tapering angle 60°

 Case II: Tapering angle (θ) = 45°

 Figure 2. Electric field profile at tapering angle 45°

 Case III: Tapering angle (θ) = 30°

Figure 3. Electric field profile at tapering angle 30°

Case IV: flat ended drift tube

Figure 4. Electric field profile at tapering angle 0°

From the Fig. 1 to Fig. 4, it is understood that the frequency and R/Q values decrease as the tapering angle of the nose increases. It is also understood that the field amplitude at the center of the gap decreases with increasing tapering angle and is minimum for the round ended drift tube nose configuration and the fields bugle more and they are more divergent as the tapering angle decreases. However, the fields are smoother and less divergent in case of flat ended drift tube nose configurations.

Table 2. Drift tube angle v/s variation in frequency and R/Q

Tapering angle (°)	Frequency (in MHz)	R/Q
60	5065.8147	67.005
45	5108.682	68.58
30	5147.901	69.07

Figure 5. Drift tube tapering angle v/s frequency variation

Figure 6. Drift tube tapering angle v/s R/Q variation

3. Modeling Aspects of Re-entrant Cavity

The design aspects of cavities are being discussed here. The optimum design of the cavity follows the choice of the beam parameter such as beam current, voltage, perveance and diameter. The main parameters involve in the design cavity resonators are the gap length, drift tube radius, diameter and height of outer concentric cylinder, shunt impedance and quality factor of the cavity and finally the coupling.

Re-entrant type resonators cavity oscillates with wavelength $\lambda/4$, $3\lambda/4$, $5\lambda/4$ etc. so height of re-entrant cavity resonator is chosen to be slightly $\lambda/4$ for the frequency range. Here λ is free space wave length. The gap length is chosen in such a way that the beam coupling coefficient is close to unity and transit angle across the gap is nearly 1 radian. It is very difficult to assess the Q and R/Q value of the cavity very accurately following conventional method. So we find these values from Computer Aided Simulation. The output coupling system is designed as per the requirements of coupling parameter.

A. Modeling of Cavity in Superfish

The cavity designed is shown in figure and voltage and stored energy is obtained from various files generated by running this program. So, R/Q is calculated by the formula $R/Q = V^2/2\omega U$ and value obtained is $\sim 114 \Omega$.

Considerable interest has been shown in extending the bandwidth of the klystron amplifier, while retaining its high gain, stability and efficiency. The theoretical analysis of multi-cavity klystron operation has met with a number of difficulties owing to the complicated nature of modulation processes involved. Account must be taken, for example, of the interaction between non adjacent cavities. As a result, the design criteria for optimum performance, such as the number of cavities required, their spacing, design and detuning from the band center, the effects of space charge and the quality of

electron beam, are only now being established.

Cavity Design results obtained:

Diameter= 26.55

Stored Energy = 3.56797E-05 Joules

$R/Q = 114$

B. Design of RF Cavity Using Magic 2D Code

MAGIC is particle-in-cell code developed by Mission Research Corporation, USA [3]. The code is available both in 2D and 3D versions. The code is capable of designing complete tube including electron gun, RF cavities, focusing field and collector as well. Following figures show the results of cavity simulation using MAGIC2D code. The resonant frequency of input cavity is shown in figure 3.

Figure 7. Electric field profile of Reentrant cavity of 5 GHz using Superfish

Figure 8. Simulation of resonant frequency of the input cavity in magic code

Figure 9. Computation of R/Q using MAGIC2D

Figure 10. Simulation of resonant frequency of the output cavity in magic code

Figure 11. Computation of R/Q using MAGIC 2D of output cavity

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Project Title: Author:

Vo [kV] Io [A] f [MHz] f [Carrier]

Unit Tube Radius [m] Beam Radius [m] Beta Pin [W]

Disks # Steps Max Iter. # Cavities

☐ Delta Frequency ☒ k
☒ Cavity Frequency ☐ DELTA^2

Cavity:	1	2	3	4	5	6	7	8	9	10
Type	1	1	1	1	1	-1	0	0	0	0
Qe	300.00	4000.00	4000.00	4000.00	4000.00	72.00	0.00	0.00	0.00	0.00
Qu	4000.00	4000.00	4000.00	4000.00	4000.00	4000.00	0.00	0.00	0.00	0.00
R/Q	114.000	114.000	114.000	114.000	114.000	114.000	0.000	0.000	0.000	0.000
d [m]	0.00350	0.00350	0.00350	0.00350	0.00350	0.00350	0.00000	0.00000	0.00000	0.00000
z [m]	0.0000	0.0500	0.1000	0.2070	0.2800	0.3245	0.0000	0.0000	0.0000	0.0000
CAVF	5000.00	4980.00	5070.00	5110.00	5090.00	5000.00	0.000	0.000	0.000	0.000
k	230.000	230.000	230.000	230.000	230.000	230.000	0.000	0.000	0.000	0.000

☐ Save as *.plt file:

☐ Save as *.out file:

☐ Save as *.dsk file:

Figure 12. RF section design results in AJ disk code.

Results of Simulation

The present design employs four intermediate cavities to increase the gain as well as bandwidth by stagger tuning and penultimate cavity to increase the efficiency.

a. Output Cavity Design

The design of the output cavity is primarily influenced by the cavity R/Q which in present case is chosen to be 90. The loaded quality factor Q_L is 72.

4. RF Section Simulation Using 1-D Code AJDISK

AJDISK is a 1-D large signal code developed by A. Jensen and is available in public domain. It is an ideal code for quickly estimating the basic design of klystron. Input needed to run the program include resonant frequency, Q_s , R/Q and gap voltage of each cavity, axial distance between the gap centers, operating beam voltage, current and drive power. The output of the program includes gain, output power, cavity voltages, phase diagram and velocity dispersion diagram.

A typical output generated by the program for design of present tube is shown in figure 3.

Figure 13. Graphical representation of beam wave interaction simulation using AJDISK

Figure 14. Phase plot of beam wave interaction simulation using AJDISK.

Figure 15. Beam current plot of beam wave interaction simulation in AJDISK

Figure 16. Velocity plot of beam wave interaction simulation using AJDISK

Output Obtained
 Gain obtained = 45.375
 Power Output Obtained = 275.813KW
 Efficiency = 0.59466

5. RF Section Simulation Using Magic Code

MAGIC is particle-in-cell code developed by Mission Research Corporation, USA. The code is available both in 2D and 3D versions. It simulates actual electric and magnetic fields by tracing the outlines of RF cavities, drift tubes and pole pieces on closely spaced grids pushing thousands of simulated electrons through these simulated fields and iterating to convergence. The code is capable of designing electron gun and cavity as well.

Following figures show the results of RF-section simulation using MAGIC code.

Figure 17. Graphical representation of RF section and Phase space for all particles

A. Magic 2D Results for 360mm RF Section Length

After simulation of RF beam wave interaction in MAGIC 2D a power of 290KW is obtained as output, which goes in accordance with our desired power.

Table 3. Input parameters for RF section of length 360 mm

CAVITY	Z (Distance in mm)	Frequency in MHz	R/Q	Qe
Cavity 1	0	5000	114	300
Cavity 2	53	4980	114	4000
Cavity 3	106	5070	114	4000
Cavity 4	216	5110	114	4000
Cavity 5	292	5090	114	4000
Cavity 6	339	5000	114	72

Figure 18. RF output power in output Cavity using MAGIC 2D for 360mm RF section

B. Magic 2D results for 345.5mm RF Section Length

Table 4. Input parameters for RF section of length 345.5 mm

CAVITY	Z (Distance in mm)	Frequency in MHz	R/Q	Qe
Cavity 1	0	5000	114	300
Cavity 2	50	4980	114	4000
Cavity 3	100	5070	114	4000
Cavity 4	207	5110	114	4000
Cavity 5	280	5090	114	4000
Cavity 6	324.5	5000	114	72

Figure 19. RF output Power ~290kW for 345.5mm RF section length

6. Conclusions

Simulation of RF cavities of 5GHz, 250 kW CW klystron has been done using POISSON and SUPERFISH CODES. Both codes results are well agreement. Beam-wave interaction simulation comparison carried out in AJDISK AND MAGIC 2D Codes. In both codes RF output power achieved greater to the desired 250 kW CW power for 5GHz Klystron. These results have been experimentally validated and well matched.

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