RF design of output resonator and conjoined input cavity with gridded electron gun for UHF Inductive output tube

*Meenu Kaushik[a,b], Ayan Kumar Bandyopadhyay[a,b] and LM Joshi[a,b]

[a]Microwave tubes division, CSIR-Central Electronics Engineering Research Institute (CEERI), Pilani, India
[b]Academy of Scientific and Innovative Research (AcSIR), India
E-mail: mkceeri@gmail.com

Abstract- **Inductive output tubes (IOTs) are widely used for broadcast and scientific applications. An IOT has only two cavities i.e. input and output, both of which serve uniquely distinct roles. The paper presents the RF design of input and output cavities for a 350 MHz, 100 kW (CW) IOT which has some important indigenous requirement for particle accelerators. CSIR-CEERI has taken-up design and development programme for this particular tube. The adopted design methodologies for both the cavity resonators are described. Besides the analytical approach, the simulation results using the codes SUPERFISH and MAGIC2D have also been presented.**

Keywords- Inductive output tube, resonator, pre-bunched beam, input/output cavity, amplifier, particle accelerators

I. INTRODUCTION

IOT is a vacuum electron tube amplifier primarily used for broadcasting applications. Its major components are similar to any other conventional vacuum tube namely, electron gun, cavity resonators, collector and focusing structure. The working principle of IOT is a cross between triode and klystron. The schematic is shown in Figure 1 [1]. The cathode is heated up to a specified temperature to produce a stream of electrons. A control grid is placed in close proximity to cathode. The input RF signal is applied to the grid. Here, the electrons are density modulated by the RF signal provided at the grid and the density modulated electron beam is pushed towards output cavity through field free drift section under the influence of DC voltage applied between cathode and anode. A suitable magnetic focusing system is used to keep the electron beam collimated in its travel from input gap to output cavity. Up to this, IOT behaves as a triode. The bunched beam then encounters an output cavity where, at the gap, the bunch induces the current in the cavity thereby exchanging the energy of beam to RF. The amplified RF is coupled out from the output cavity through proper arrangement and the decelerated spent beam goes to the collector for dumping. The output section of IOT is similar to a klystron. Considering the design features of IOT as a combination of triode and klystron, IOT is also named as 'klystrode', a trade name given by Eimac division, CPI [2].

IOT is used in broadcast applications as UHF TV transmitters for decades. Its high efficiency, high linearity and low operating cost make this device suitable for communication purposes. But, for over last one decade, it has evolved as a tough competitor for the accelerators applications too. Many high powered accelerators such as Diamond, CERN, LANSCE and ALBA use IOT as RF source [2, 3]. The compactness, reliability and higher efficiency make this device desirable for this application area.

The paper deals with the design approach adopted for the cavity resonators for a 350 MHz, 100 kW (CW) IOT required for proton accelerator application. The cavities are the key components responsible for proper beam modulation and efficient RF amplification.

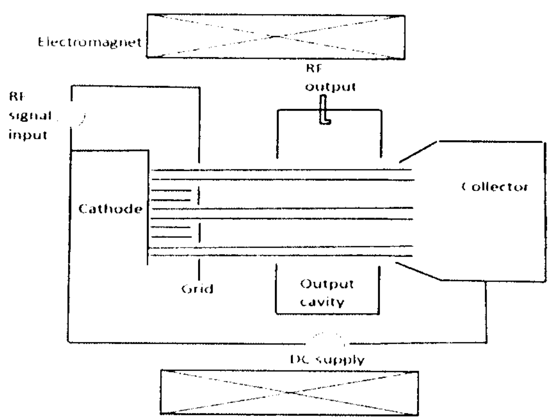

Figure. 1. Schematic of IOT.

II. DESIGN APPROACH ADOPTED FOR INPUT CAVITY

The input cavity is the most critical component in IOT as it is not an independent entity. The input cavity is integrated with the electron gun to produce the pre-bunched beam from the input section. The interaction gap for electron beam and input RF is the cathode-grid gap. Therefore, the RF is applied at the grid. The 2D view of realizing this cavity is shown in Figure 2. The cavity's inductance, capacitance and resonant frequency can be estimated from the following equations (1-3) [4].

$$L = \frac{\mu l}{2\pi}\ln(b/a) \tag{1}$$

$$C = \epsilon_0[\frac{\pi a^2}{d} - 4a\ln(0.765/\sqrt{\{l^2 + (b-a)^2\}})] \tag{2}$$

$$f_r = \frac{c}{2\pi\sqrt{\epsilon_r}\sqrt{\{al\left[\frac{a}{2d} - \frac{2}{l}\ln\left(\frac{0.765}{\sqrt{[l^2+(b-a)^2]}}\right)\right]\ln\left(\frac{b}{a}\right)\}}} \tag{3}$$

where, L is the inductance produced in the cavity wall, μ is the permeability, C is the capacitance in the cavity gap, ϵ_0 is the permittivity of free space, f_r is the resonant frequency, ϵ_r is the relative permittivity of the material of the cavity, a and b are radii of inner and outer conductor respectively, d is the cathode-grid gap, l is the height of the cavity and $c = 3\text{x}10^8$ m/s is the velocity of light in vacuum.

The idea of adopting this structure is as follows: A coaxial type narrow-gap resonator has been chosen. As it has to position itself onto the gridded electron gun, it must envelope the cathode, beam focusing electrode (BFE) and grid. The inner solid conductor houses the cathode hence; the outer radius of this conductor should be greater than the cathode disk radius. The cathode disk radius will be calculated by the standard Vaughan's synthesis approach [5].

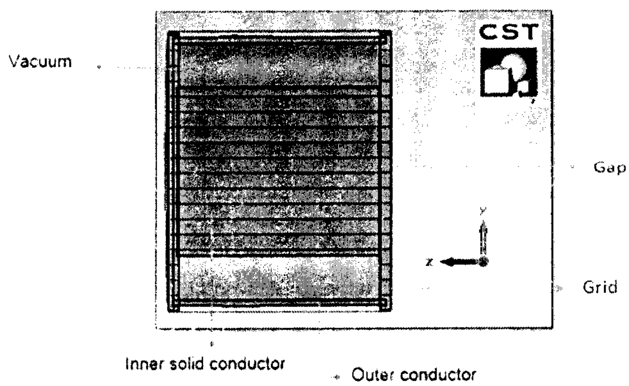

Figure. 2. Basic visualization of input cavity structure.

The gap is very narrow around ~ 0.3 mm. The electron beam interacts with 0.25 radians of RF cycle so that the beam will encounter a constant RF field within this gap. This further leads to the density modulation of the beam. Increasing this gap is not affordable as the transit time of electrons will become greater than the RF time period and this condition will result in no exchange of energy. On the contrary, decreasing this gap can cause electrical breakdown between the electrodes. Hence, the gap is optimized at 0.3 mm within safe limits. The outer conductor's radius will decide the resonant frequency of the cavity. The height of cavity is optimized as multiple of λ (wavelength of RF). The cavity is simulated in SUPERFISH code as shown in Figure 3. The E field maximizes at the narrow gap as shown in Figure 4.

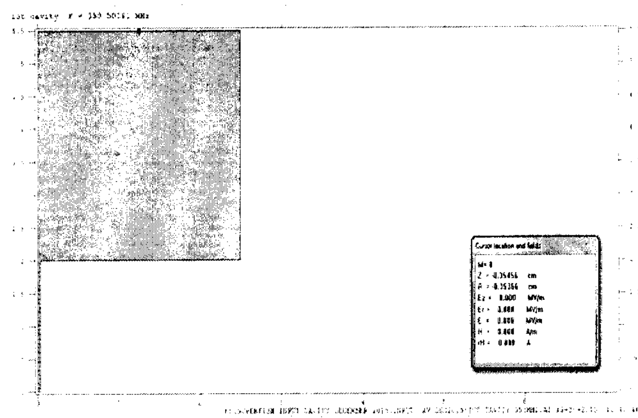
Figure. 3. Input cavity resonating at 350 MHz.

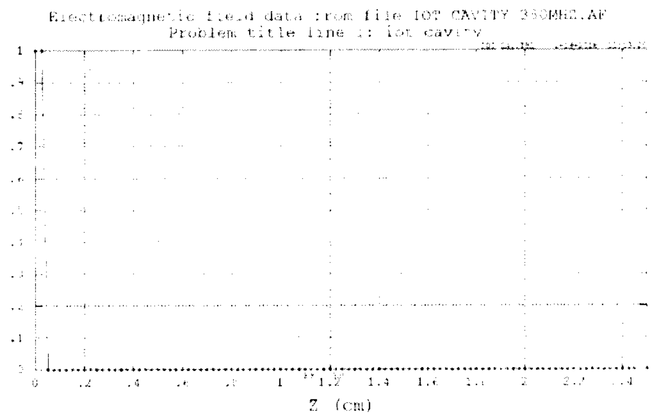

Figure. 4. E_z field in cavity.

The breakdown limit of this narrow gap of 0.3 mm is 2.1 kV. From SUPERFISH, the cavity stored energy is found to be $1.81936e^{-6}$ J and E_z is 0.375 kV/m. Hence, the R/Q is obtained to be 17.5 Ω.

Though, this structure has given substantial idea for integrating the gun with the cavity, but some more points should be considered including how to insert and place BFE so that the fields will not get disturbed inside the cavity. The placement of actual grid should also be there in front of the cathode to figure out if RF within the gap still exists. The improved design of input cavity relating more to practicality is shown in Figure 5 [6]. The BFE and grid are housed in it providing a real picture of expected input cavity. The simulations of this model are in progress.

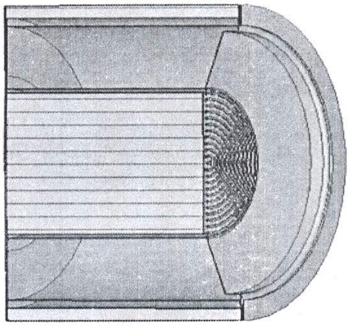

Figure. 5. Improved practical design of input cavity.

III. ANALYTICAL AND COMPUTER AIDED DESIGN (CAD) OF OUTPUT CAVITY

The main features making IOTs popular these days are: high efficiency, compactness and cost-effectiveness. As we can see from the schematic provided in introduction section, IOT has only one physical cavity i.e. the output cavity. Hence, it is obvious to comprehend the compactness of this device. The IOT output cavity is similar to a klystron cavity i.e. a re-entrant cavity. The inductance, capacitance and resonant frequency for this resonator are given by the following equations (4-6) [4].

$$L = \frac{1}{\pi\omega}\sqrt{\frac{\mu}{\epsilon}}\ln\frac{b}{a}\tan(\beta l) \quad (4)$$

$$C = \frac{\epsilon\pi a^2}{d} \quad (5)$$

$$f_r = \frac{1}{2\pi\sqrt{\omega C}} \quad (6)$$

where, symbols have their usual meanings.

The important parameters to optimize are the radius and length of outer conductor and nose cones dimensions i.e. the radius and drift gap of the cavity. The height of cavity is chosen to be quarter wavelength and the inner radius of outer conductor is optimized to get the desired resonant frequency. The nose cone's inner radius (also termed as tunnel radius) is calculated using standard analytical formulae [6], considering a beam fill factor of about 70% for proper coupling of electron beam and RF wave. The drift gap is calculated such that beam faces a constant retarding electric field in the gap to deliver its energy to the RF for amplification. The cavity operating mode is TM_{010}. The simulation of output cavity has been carried out in MAGIC2D code and the results are presented in Figures 6-8. The obtained Q and R/Q are 74 and 148 Ω respectively.

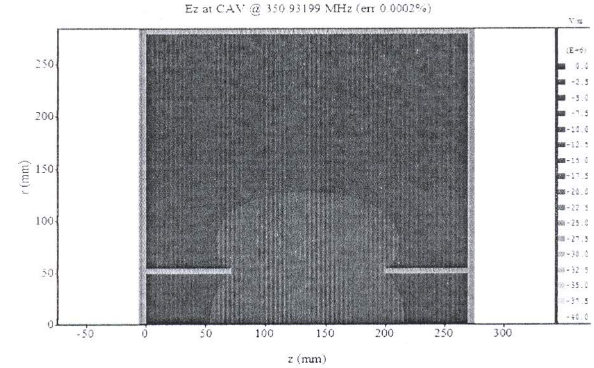

Figure. 6. Eigen-mode analysis of output cavity operating at 350 MHz.

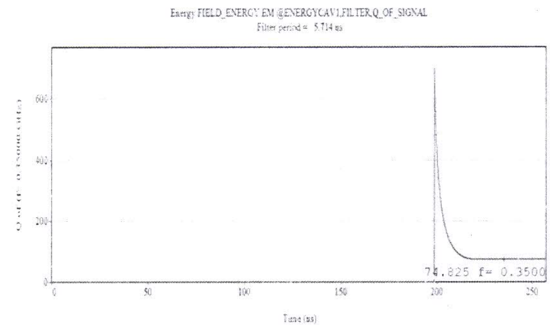

Figure. 7. Q factor of output cavity (~ 74).

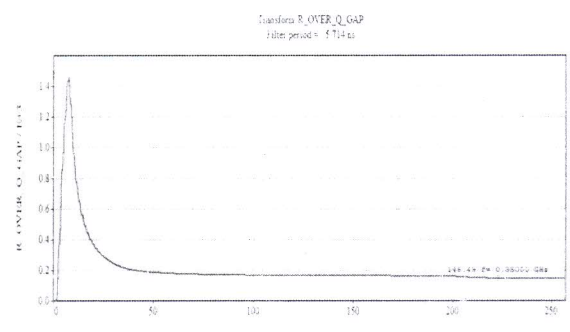

Figure. 8. R/Q of output cavity (~ 148 Ω).

CONCLUSION

For a 350 MHz IOT, the analytical and simulation results of input and output cavities are discussed in the paper. As input cavity is very critical to realize practically, the layout of the integrated model is depicted and conceptualized. The output cavity is designed and optimized successfully. Improper functioning of cavities affects the amplification process. Hence, their appropriate design is vital.

ACKNOWLEDGMENT

Authors are thankful to the Director, CSIR-CEERI for allowing us to present the work.

REFERENCES

[1] Meenu Kaushik, LM Joshi, "RF design of input cavity structure of a low frequency, high average power IOT", PIERS proceedings, Prague, Czech Republic, July 6-9, 2015.

[2] Rebecca Seviour, "Comparative overview of inductive output tubes", ESS accelerator division report, June 2011.

[3] P Sanchez et al., "The ALBA RF amplifier system based on inductive output tubes (IOT)", Proceedings of EPAC'08, Italy.

[4] Samuel Y Liao, "Microwave devices and circuits", Handbook, Pearson education, pp 344-345.

[5] JRM Vaughan, "Synthesis of the Pierce gun", IEEE Trans. Electron Devices, Vol. ED-28, No. 1, pp 37-41, 1981.

[6] Meenu Kaushik, Ayan Kumar Bandyopadhyay and LM Joshi, "Theoretical design of the gun-cum-input cavity and focusing structure envisaged for a 350 MHz, 100 kW (CW) inductive output tube", Journal of Electromagnetic waves and applications, Taylor and Francis, August 2016, http://dx.doi.org/10.1080/09205071.2016.1223557.