Design of Liquid Face Cooled Double-Disc Window for Gyrotron

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Abstract- **The design of face cooled double disc window for 42 GHz, 200 kW Gyrotron has been carried out using the CST microwave studio. In this design double discs D1 and D2 of diameter 85 mm and thickness 3.2 mm sapphire window and spacing of discs 2.7 mm have been used in the simulation and sapphire discs are face cooled by Coolant FC-75. The return loss (S11) and transmission loss (S21) of the 42 GHz Gyrotron window have been found -40.3 dB and -0.04 dB respectively. The double disc face cooled structure causes power loss in two discs. In addition, loss in the coolant also has to be taken into account. However, as far as cooling of dielectric is concerned this design is the most effective. The reflection and absorption of RF power depends on the dielectric properties of sapphire as well as coolant liquid. The window geometrical parameters are optimized considering the minimum return loss and the minimum insertion loss by using CST microwave studio. The thermal design of the face cooled window during extreme case of operation, i.e. at saturation has been carried out using ANSYS software and discussed in the paper. The temperature range on the sapphire disc surface has been found to be 35^0C - 80^0C. The temperature range on the window disc surface has been found satisfactory. The RF window optimized design allows low heat loads in the ceramic and consequently low temperature increase and low stresses. The power handing capacity of face cooled window has been determined by ANSYS. This design of RF window is capable of handling the thermal and mechanical loading in a 200 kW output power.**

Keywords- RF Window; Thermal Analysis; Stress; Cooling Channel; Heat Flux

I. INTRODUCTION

Gyrotron is a high power microwave tube, which emits coherent radiation at approximately the electron cyclotron frequency or its harmonics. Gyrotron is widely used in plasma fusions, ECRH heating, industrial heating and material processing [1]. The need for high power, high frequency rf sources for the magnetic fusion research experiments has provided much of the impetus for the development of present day gyro oscillators. From the last three decades gyrotron oscillators have played a key role in magnetic fusion experiments. Magnetic confined plasma fusion is the most important application of gyrotron oscillator as a high power, high frequency rf source [2]. A 42 GHz, 200 kW (CW) gyrotron is being developed for electron cyclotron resonance plasma heating for an Indian TOKAMAK system. RF window is a most critical component of high power microwave tubes and is used on the output section of the device for the extraction of RF power from vacuum to external pressurized atmosphere environment. RF window is also used as a vacuum seal of the microwave tube, which limits its power handling capability. RF window must be fabricated from a low-loss material, which is also suitable for ultra-high vacuum application. The desired features of an ideal window are minimum reflection, minimum insertion loss, and high power handling capability, wide bandwidth, excellent mechanical strength, high thermal shock resistance, high thermal conductivity and vacuum tightness. Gyrotron window is needed capable of transmitting significant amount of microwave energy without exhibiting thermal runway. The window must be able to withstand the thermally induced stresses caused by the temperature rise of the window as well as the mechanical stresses. In the Gyrotron, different types of window according to the various cooling schemes are used for the extraction of RF power. Generally, windows with multiple dielectrics with distributed cooling double disk with surface cooling by liquid, single disk with surface cooling by gas and single disk with edge cooling are used in Gyrotron. The gyrotron operating at 24-70 GHz, generally uses double disc RF window which allows surface cooling to keep the disc temperature below a safe limit. But it is always preferable to use single-disc edge cooled window because of its simplicity of fabrication and reliability. The double disc face cooled structure causes power loss in two discs. In addition, loss in the coolant also has to be taken into account. However, as far as cooling of dielectric is concerned this design is the most effective. In the double disc window, two discs are required per barrier with a spacing of approximately one wave length and some power is absorbed by dielectric cooling liquid, which are disadvantages of this types of window [3].

Ultimately, the high power limits for all RF window is a results of heating caused by absorbed microwave energy in the window. Even though the fraction of energy absorbed is quite small, on the order of 0.1% for typical materials of interest, the large amounts of transmitted power means that even a small fraction can result in significant heating leading, thermal stress and thermal runaway. In the heated RF window structure thermal energy generation is initiated by absorbed microwave energy. This energy is removed in steady state operation by thermal conduction and force convection. The conduction temperature profile is important because it ultimately leads to failure of the window when the power is high. The temperature gradients required to drive thermal energy out of the window cause different areas of the window. As window heats up, these stresses will reach the ultimate strength for the given material and surface of geometry and the window will fail.

II. ELECTRICAL ANALYSIS

RF window is a most critical component of high power Gyrotron and is used on the output section of the device for the extraction of RF power from vacuum to external pressurized atmosphere environment. RF window is also used as a vacuum seal of the microwave tube, which limits its power handling capability. In 42 GHz, 200 kW Gyrotron double discs D1 and D2 of diameter 85 mm and thickness 3.2 mm sapphire window and spacing of discs 2.7 mm have been used in the simulation and sapphire discs are face cooled by Coolant FC-75. RF window disk thickness and diameter are optimized considering the minimum return loss and the minimum insertion loss by using CST microwave studio [4]. Performance of a RF window critically depends on the dielectric properties such as permittivity, loss tangent etc. of window material and cooling liquid. The loss tangent and permittivity of window material and cooling liquid affect the absorption and the transmission of RF power [5].

The dielectric materials sapphire and boron nitride are used in electrical design for low power Gyrotron window. The window disk thickness *d* is determined so that the power reflection is minimum and power handling capability is high. To avoid the reflections of an incident wave from the window disk, the thickness *d* should be equal to an integer multiple of half-wavelength corresponding to the operating frequency ($d = n\lambda/2\varepsilon_r^{1/2}$, where n is an integer, λ is the free space wavelength and ε_r is the permittivity of window material). The reflection and transmission of the window disk are independent from the diameter as the wavelength is quite small compared to the disk diameter [6]. Once the dielectric and the coolant are decided, for a particular frequency and power, it is necessary to decide the respective thicknesses for proper matching. Tentative values are obtained analytically as well as by simulation. The main objective is to ensure that the power reflected by one material-discontinuity interferes destructively with that from the other. Once the thickness of the coolant is confirmed, the flow rate can be decided based on the heat transfer requirements. Table 1 shows the electrical design parameters of RF window for 42 GHz Gyrotron. Fig. 1 shows the schematic diagram of double disc sapphire window using for 42 GHz Gyrotron. The scope of sapphire or other dielectric based high-power window operating at more than hundred GHz and capable of handling average power of one mega watt minimum .The material of disc is sapphire and dielectric constant (ε_r) of the sapphire is 9.41, loss tangent is 5.4×10^{-5} and dielectric constant of FC-75 is 1.8 and loss tangent ($\tan\delta$) is 26×10^{-4}. Fig. 2 shows the CST model of double disc RF window with coolant FC-75 for 42 GHz Gyrotron [7].

TABLE 1 ELECTRICAL DESGIN PARAMETERS OF RF WINDOW

Parameters	Values
Disc Diameter (R)	85 mm
Disc Thickness (L)	3.2 mm
Gap of disc (coolant)	2.7 mm

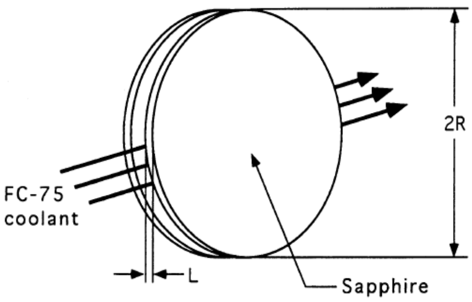

Fig. 1 Schematic diagram of double disc window

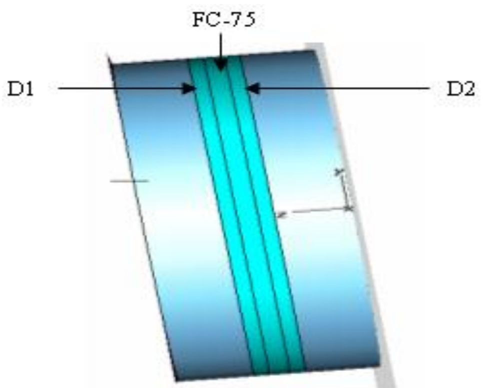

Fig. 2 CST model of double disc window with coolant for 42 GHz Gyrotron

The performance of the S-parameters for face cooled window with respect to frequency is shown in Fig. 3. The S parameter simulations for the optimized RF window show very small reflection and absorption in the RF power. The maximum temperature of the gyrotron window depends on the RF power absorbed in the disk.

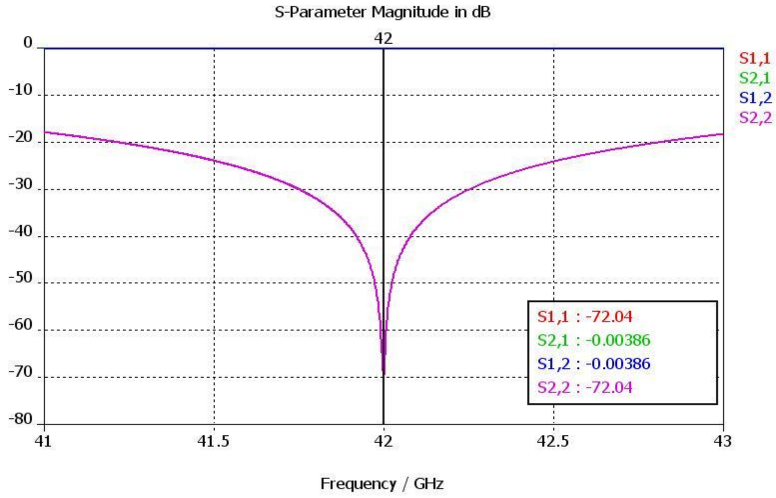

Fig. 3 S-parameters performance of the face cooled RF window using CST

III. THERMAL AND STRUCTURAL ANALYSIS

On the basis of electrical design of RF window, the thermal and structural analysis is performed by using finite element analysis code ANSYS v.11.1 [8]. The objective of thermal analysis is to assess the temperature distribution, axial stress, radial stress and thermal expansions in the RF window for the 42 GHz Gyrotron during extreme case of operation, i.e. at saturation, this means at maximum power of 200 kW. A transient thermal analysis is used to determine the temperature distribution as a function of time. RF transmission loss of 10 W on ceramic window is taken as heat load, which is estimated by considering low insertion loss in the window assembly of 200 kW of the tube. Input parameters used in simulation are material property, coolant property, heat flux, film coefficient and bulk temperature. Input parameters of the window for thermal analysis are shown in Table 2. Fig. 4 shows the geometry of cooling channel designed around the window outside surface for proper cooling of the window. For passing coolant, the window will have two male type 0.5 inch quick release couplings, one for the inlet and the other for the outlet. Table 3 shows the materials properties used for window assembly. For thermal analysis the window boundaries consist of two parallel of faces are of which is isolated and heat flow across the other face is given by equation.

$$q = h\,(T_s - T_b)$$

Where h is film coefficient, T_s the surface temperature of the disc and T_b bulk temperature of the coolant. The edges of the sapphire disc are assumed to be isolated.

TABLE 2 INPUT PARAMETERS FOR THERMAL ANALYSIS

Parameters	**Values**
Loss tangent	0.0002
Bulk temperature	25^0 C
Water flow rate	5 L/min
Film coefficient	8184(W/m^2 ^{0}C)
Input power	250 kW

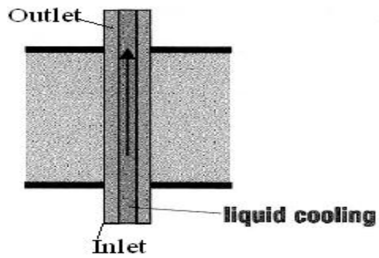

Fig. 4 Geometrical design of the liquid cooling

TABLE 3 PROPERTIES OF DIFFERENT DIELECTRIC MATERIALS

Parameters	Alumina	Sapphire
Thermal Conductivity (W/m.K)	25	38
Density (kg/m^3)	3900	3980
Specific heat (J/kg.K)	850	764
Emissivity	0.25	0.6
Loss tangent ($\tan\delta*10^{-5}$)	20	5.4
Young's modulus (GPA)	330	385
Coefficient of thermal expansion	8.0	5.5
Poisson ratio	0.21	0.29

The temperature distribution on window obtained using 3D thermal analysis. For an initial coolant temperature of 200 K the maximum power handling capability of the window is limited to 300 kW because 290 K is the water bulk temperature [9]. The structural analysis has been used to determine the displacements and stresses in window caused by heat loads. The material properties required for structural analysis are Young's modulus, Poisson's ratio and coefficient of thermal expansion. The finite element stress analysis of RF window was performed on the inner disc. This disc has higher pressure loading due to the internal vacuum of the Gyrotron tube. The 3-D stress analysis indicates that the double disc is operating close to its maximum stress level. The largest stress contribution comes from the mechanical loading of the discs by the coolant pressure. The large tensile stresses are compensated to a limited extent by the thermal stresses which arise during Gyrotron operation. The maximum radial tensile stress of 152 MPa occurs near the window. The maximum compressive stress is 250 MPa. The maximum stress develops on the center of sapphire disc. The output results of the temperature distributions and different stresses on some typical parts are obtained from the ANSYS v.11.1 software. From these results, it is clear that the deformations in the parts are within the safe limit under the operating condition.

The thermal and structural analyses have been carried out for the estimation of temperature distributions and resulting stress developed on the RF window using ANSYS. Fig. 5 shows the temperature distributions on the sapphire disc window for different heat flux. During the transmission of a TE_{03} Mode for 200 kW Power, the temperature increases at the center of the window. Table 4 shows the temperature distributions have been obtained at different dielectric loss and heat flux. Fig. 6 shows the temperature profile verses coolant flow rate. When coolant flow rate increased, temperature on the disc will be reduced. In the simulation heat generation rate in window is adjusted at each time step to account for the temperature dependence of loss tangent. The maximum temperature rise time 98% is approximately 1.0 second for face cooled window at the center. Fig. 7 shows the transits response of the face cooled double disc window. The maximum temperature rise decreases with frequency due to loss tangent inversely proportional to the frequency.

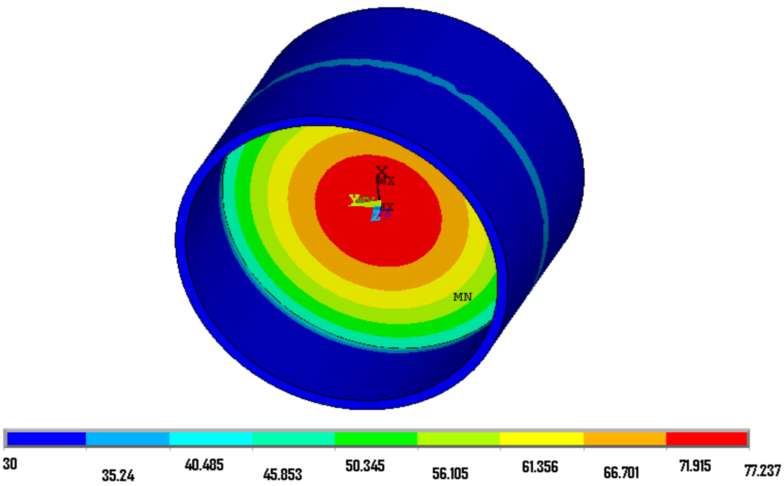

Fig. 5 Temperature distribution on disc with heat flux 10370.5 (W/m^2)

TABLE 4 TEMPERTURE PROFILE VERSE HEAT FLUX

Dielectric loss (W)	Heat Flux (W/m^2)	Temperature(°C)
25.0	2550.6	30.0-58.5
40.0	10370.5	34.1-77.5
50.0	25455.6	35.7-96.7

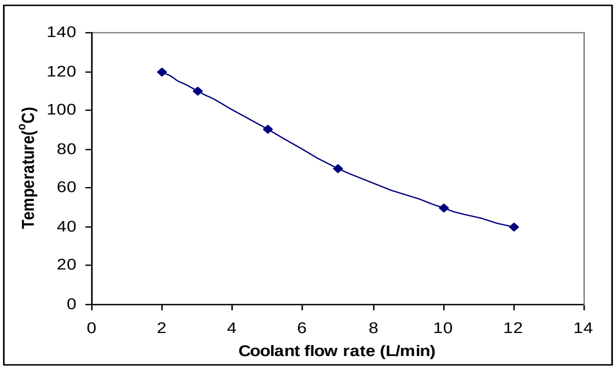

Fig. 6 Temperature profile verses coolant flow rate

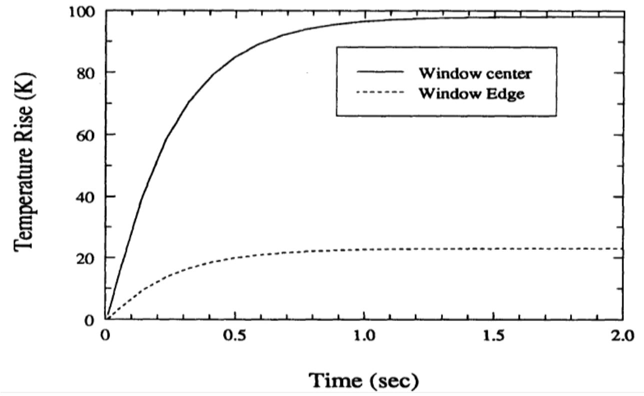

Fig. 7 Temperature response with respect to time for window

IV. CONCLUSIONS

In 42 GHz gyrotron double disc of diameter 85 mm and thickness 3.2 mm sapphire window and coolant FC-75 of discs 2.5 mm has been used in the simulation. In the presented design, the temperature on the disc of RF window does not exceed 100^{o}C and found in safe limit. The subsequent thermal stresses do not deteriorate it. The RF window optimized design allows low heat loads in the ceramic and consequently low temperature increase and low stresses. In conclusion, it has been established that there are RF window designs available capable of handling the thermal and mechanical loading in a 200 kW CW power Gyrotron.

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