Design & Simulation of Double Disc Sapphire RF Window for High Power 42 GHz, 200 kW Gyrotron

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Abstract— **RF window is an important component of all high power microwave tubes and is used on the output section of the device for the propagation of RF power from ultrahigh vacuum environment to external normal pressure environment. There are different types of windows used for Gyrotron. This work presents the design & simulation of double disc sapphire window with surface cooling for 42 GHz, 200 kW Gyrotron using HFSS software and also analyzes the losses for variation in disc thickness & variation in spacing between two discs with two different coolants like FC-75 and FC-40. The minimum Insertion loss (S21) & return loss (S11) is found to be -0.01 dB & -25.20 dB respectively for disc thickness 3.2mm and optimized spacing 2.1mm of RF window with FC-40 coolant for 42 GHz Gyrotron.**

Index Terms— **RF window, Gyrotron, Double disc sapphire window, Coolant FC-40, Coolant FC-75, HFSS software.**
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I. INTRODUCTION

A Gyrotron is a high powered vacuum tube which generates millimeter-wave electromagnetic waves by bunching electrons with cyclotron motion in a strong magnetic field. The Gyrotron oscillators are widely used in the various fields of science and technology like high speed communication, material processing, biological imaging, plasma diagnostics, NMR spectroscopy and electron cyclotron resonance heating (ECRH) in the plasma fusion. RF window is a critical component of all high power microwave tubes and is used on the output section of the device for the propagation of RF power from ultrahigh vacuum environment to external normal pressure environment. The RF window is a passive component that must be transparent to microwaves and hold ultra high vacuum [1]. 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 and vacuum tightness [2]. And low loss material should be suitable for fabrication of RF window. The wave-guide type microwave windows are generally preferred for high power microwave tubes due to their higher capacity for handling high peak and average RF power. The other functional advantages are broad bandwidth and easy impedance matching with the rest of the transmission line [1].

II. DESIGN OF DOUBLE DISC SAPPHIRE WINDOW

In the Gyrotron, different types of window according to the various cooling schemes are used for the extraction of RF power. These are: (i) Multiple dielectrics with distributed cooling, (ii) Single disc with edge cooling, (iii) Single disc with surface cooling by gas and (iv) Double disc with surface cooling by liquid [3]. Each of these designs possesses its own advantages and disadvantages. For high power CW gyrotrons at millimeter wavelengths, advanced materials such as sapphire, chemical vapor deposited (CVD) diamond, Silicon nitride composite, BeO, Au-doped silicon etc. have to be used. Design of CVD diamond, sapphire or other dielectric based high-power window operating at more than hundred GHz and capable of handling average power of one up to two megawatts [4]. The gyrotron operating at 24-70 GHz generally uses double disc RF window that allows surface cooling to keep the disc temperature below a safe limit.

Here we present the design & simulation of double disc sapphire window for 42 GHz gyrotron. The development of the high power and high frequency window is extremely depending on the dielectric characteristics like loss tangent and permittivity, of the window material. The loss tangent and permittivity of window material affect the absorption and transmission of RF power [5]. In 42 GHz gyrotron **double disc sapphire window** with surface cooling have been designed and **coolant FC-40** between two discs have been used. The electrical design parameters for the window are thickness, diameter, length of the waveguide and dielectric constant of the disc. The window disk thickness *d* is determined such 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 [6]

$$d = n\lambda/2\varepsilon r^{1/2} \qquad (1)$$

Where *n* is an integer, λ is the free space wavelength and *εr* 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 compare to the disk diameter. It is necessary to decide the respective thicknesses for proper matching after dielectric and the coolant are decided, for a particular

frequency and power. By calculating thickness theoretically from equation (1), we obtain *d* as 3.4mm for n=3. By simulating for various values of *d* we have obtained better results for d=3.2mm rather 3.4mm. So we have considered the optimized value, d=3.2mm for our further simulations. As the inner diameter of our 42 GHz Gyrotron is 85mm, we have taken the double disc of diameter 85mm and the spacing between two discs has been optimized using simulation in HFSS as 2.1mm, which is shown in fig.3. The design of RF window (double disc sapphire window) for TE03 mode has been carried out using Ansys HFSS (high frequency structure stimulator) software. The sapphire base window operating for TE03 mode has been used in 42 GHz gyrotron. The material of disc is sapphire and dielectric constant (ε_r) of the sapphire is 9.41, loss tangent is 5.4×10^{-5}. The spacing between discs is Coolant FC-40. The dielectric constant & loss tangent of FC-40 is 2.1 & 0.017 respectively and dielectric constant & loss tangent of FC- 75 is 1.8 & 0.020 respectively [7].

The parameters of RF window have been optimized using simulation in HFSS, which are shown in table 1.

Table 1: Optimized design parameters of double disc sapphire window

Sr.No.	Parameters	Value
1	Disc diameter (D)	85 mm
2	Disc thickness (d)	3.2 mm
3	Spacing between two disc (s)	2.1 mm
4	Window length (L)	40 mm
5	Operating frequency (f)	42 GHz

III. SIMULATION OF DOUBLE DISC SAPPHIRE WINDOW) USING HFSS

To design double disc sapphire window for TE$_{03}$ mode of high power gyrotron in HFSS, it's necessary to make 1/10th section (36 ° section) of main design module of RF window. In HFSS one limitation is there that the all higher TE$_{0n}$ modes are not available when the design module with full 360 ° position because only 25 number of modes are available, but when makes 1/10th (36 ° section) portion of main design module the higher TE$_{0n}$ modes are available. Doing this steps in HFSS the correct result don't affected. Fig. 1 shows the main design module of RF window with 360 ° position, and Fig. 2 shows the 1/10th section (36 ° section) of main design module. It is also necessary to assign some basic input parameters like wave ports, which are given as excitation with specific number of modes (max up to 25) to both the ports of the waveguide, to assign specific boundaries to the module of window. In solution setup we kept solution frequency at 42 GHz, and in adaptive solution we kept maximum number of passes and maximum delta S at 6 and 0.02 respectively. We also assigned frequency sweep 41 to 43 GHz range. In HFSS, the input field source kept at 200kW for electric & magnetic field plot of RF window.
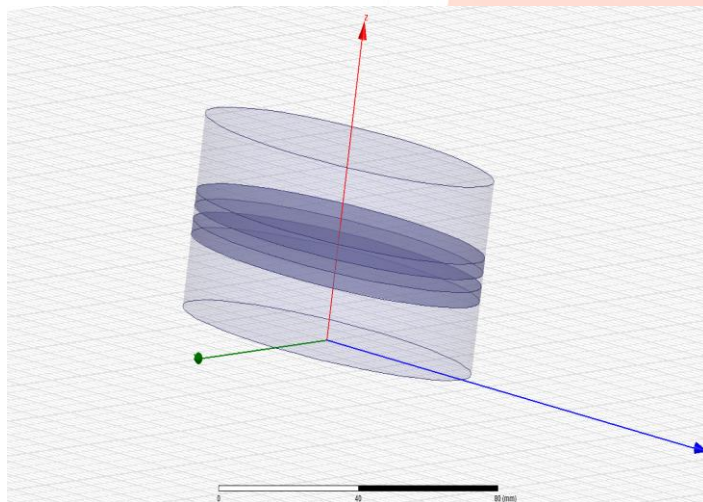

Fig.1 Main design module of double disc sapphire window in HFSS (all dimensions according to Table 1)
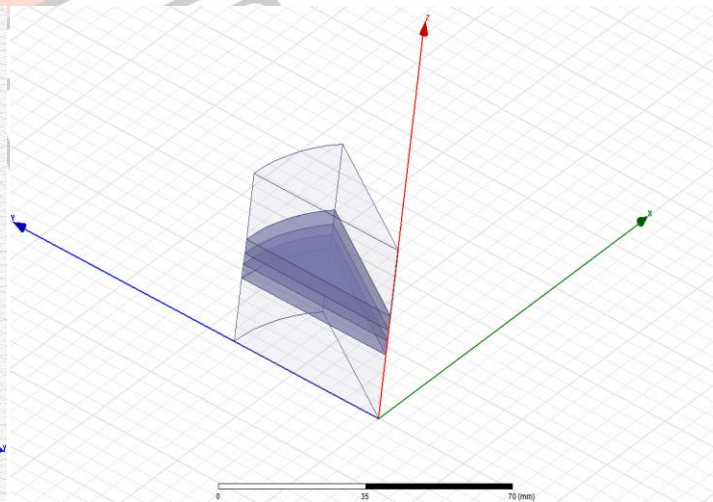
Fig.2 1/10th section (36 ° section) of main design module (shown in fig.3) of RF Window

IV. SIMULATION RESULTS USING HFSS

All simulation results of RF window in HFSS shown in below figures. We get TE$_{03}$ mode pattern for RF window at mode number 5 in HFSS which shown in Fig.3. Figure 4 shows the insertion & return loss in RF window (with FC-40) at 41 to 43 GHz

frequency range. We got minimum insertion loss S21 -0.01dB & return loss S11 -25.20 dB for RF window at operating frequency 42 GHz.
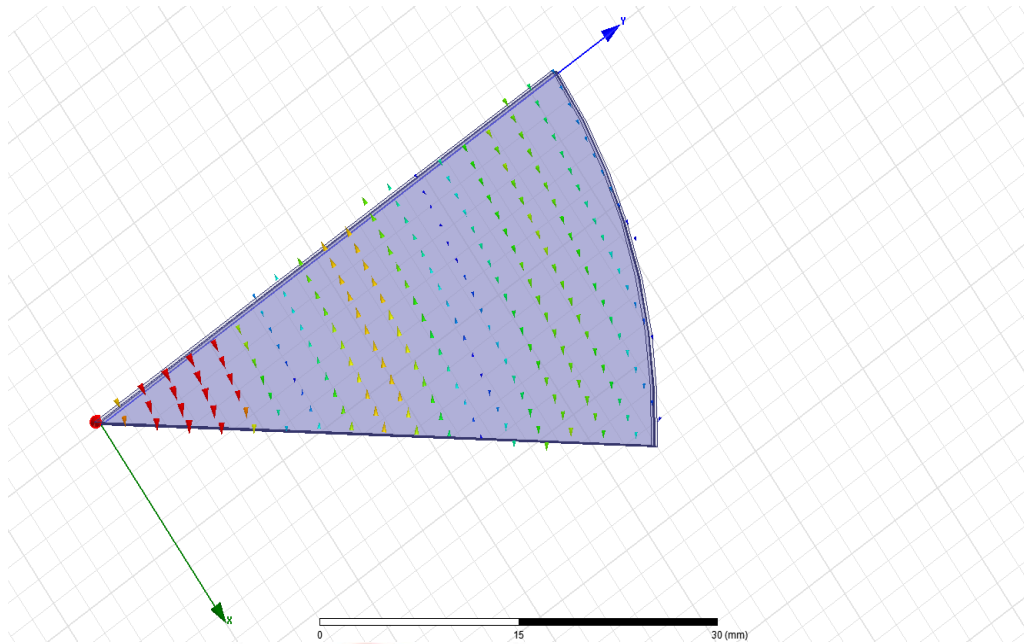

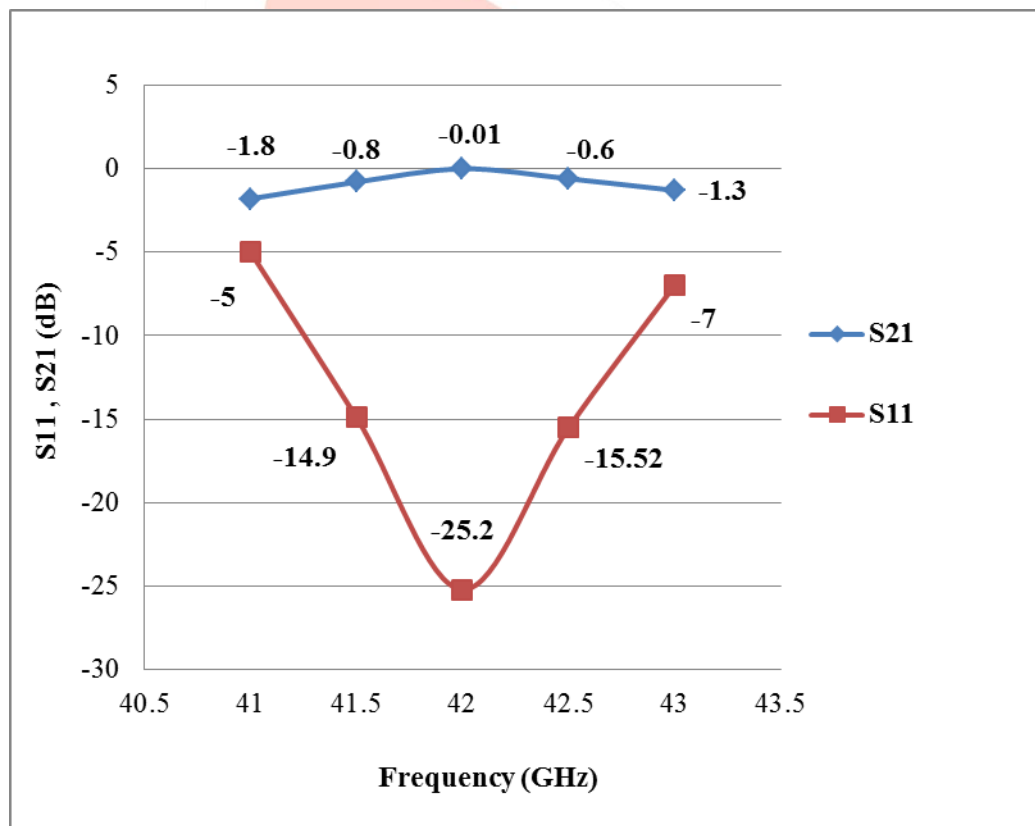Fig. 3 TE03 mode pattern for RF window

Fig. 4 Insertion loss S21 & Return loss S11 (for d= 3.2mm & s= 2.1mm) at 41 to 43 GHz range

Figures 5 & 6 show the Return loss and Insertion loss performance when vary the spacing (coolant FC-40) between two sapphire discs. As we increase the space between two discs insertion loss and return loss increase, which is shown in the below figures (5 & 6). If we keep 2.1mm space between two discs then minimum losses are achieved. The spacing (Coolant FC-40) between two discs has been optimized using HFSS software.
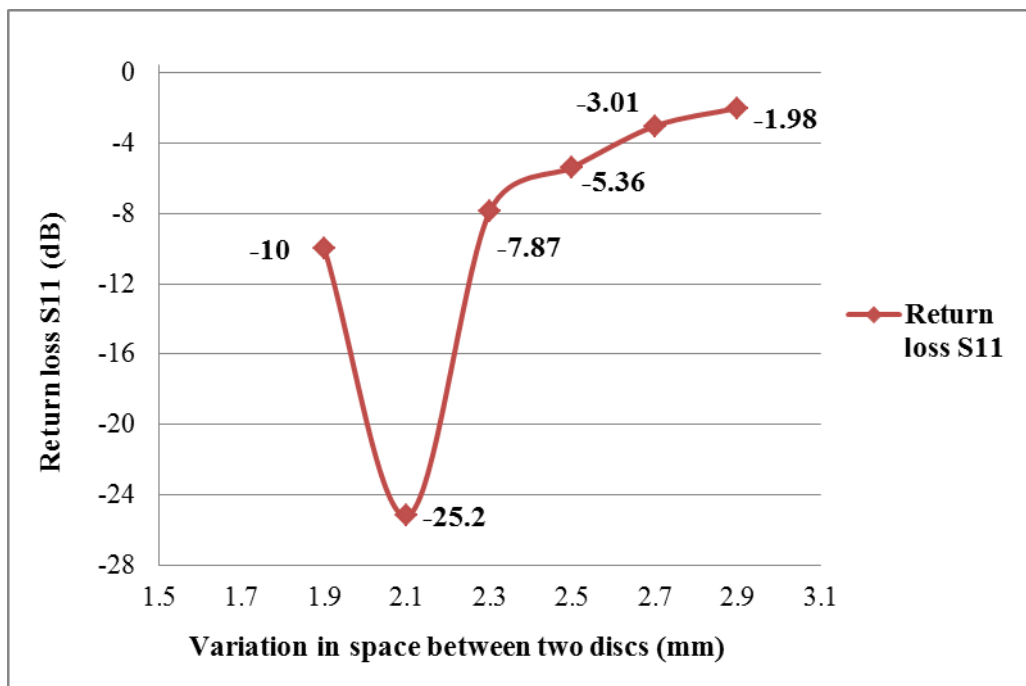
Fig. 5 Return loss S11 at variation in spacing (coolant FC- 40) between two discs (d = 3.2 mm)
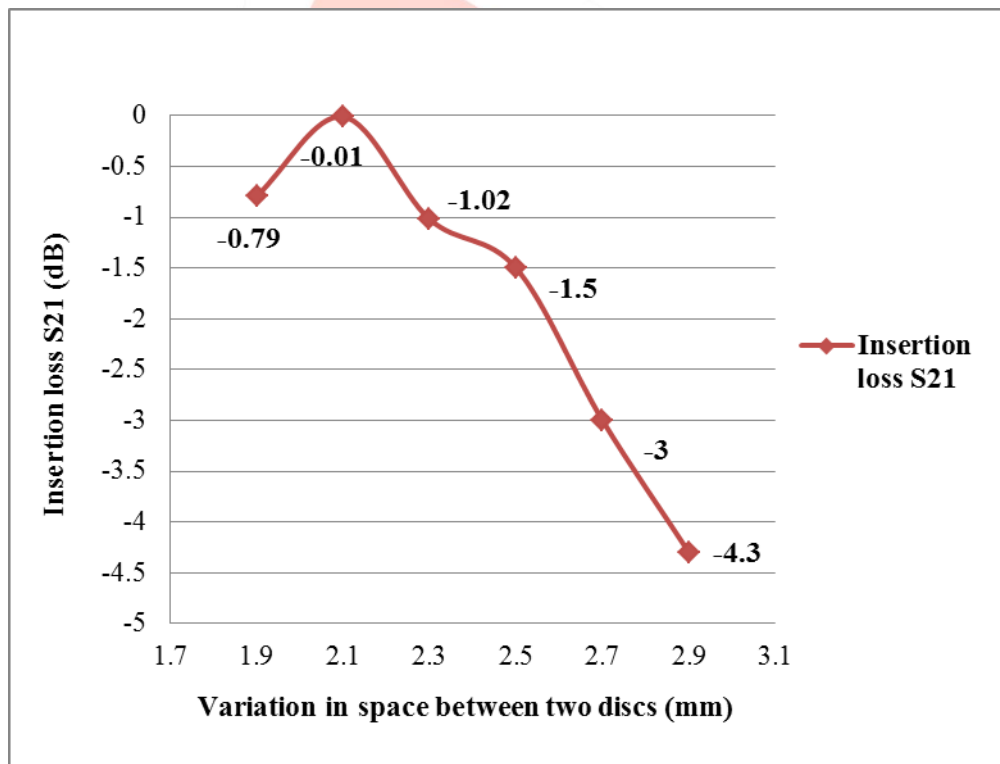

Fig. 6 Insertion loss S21 at variation in spacing (coolant FC- 40) between two discs (d = 3.2 mm)

Figures 7 & 8 show the magnitude & distribution of electric field & magnetic field in double disc sapphire window for 200 kW with disc thickness of 3.2 mm, 2.1 mm spacing (FC-40 coolant) between two disc.
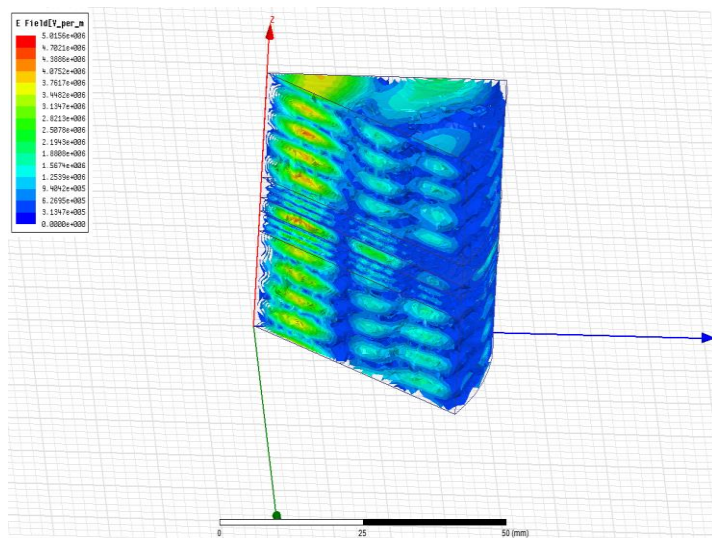
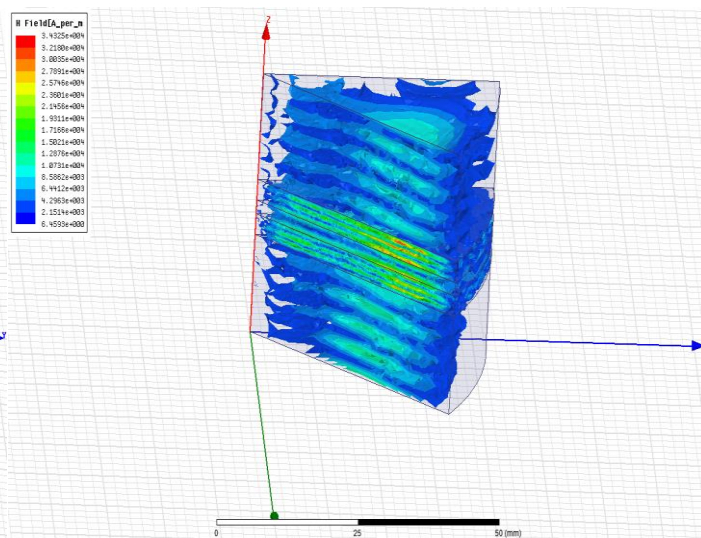Fig. 7 Electric field in RF window (with FC-40) in HFSS

Fig.8 Magnetic field in RF window (with FC-40) in HFSS

Figure 9 & 10 shows the Return and Insertion losses performance by varying the space **(coolant FC-75)** between two sapphire discs. The spacing (**Coolant FC-75**) between two discs has been optimized using HFSS software. As we inecrease the space between two discs insertion loss and return loss inecrease, which is shown in above figures (9 & 10).
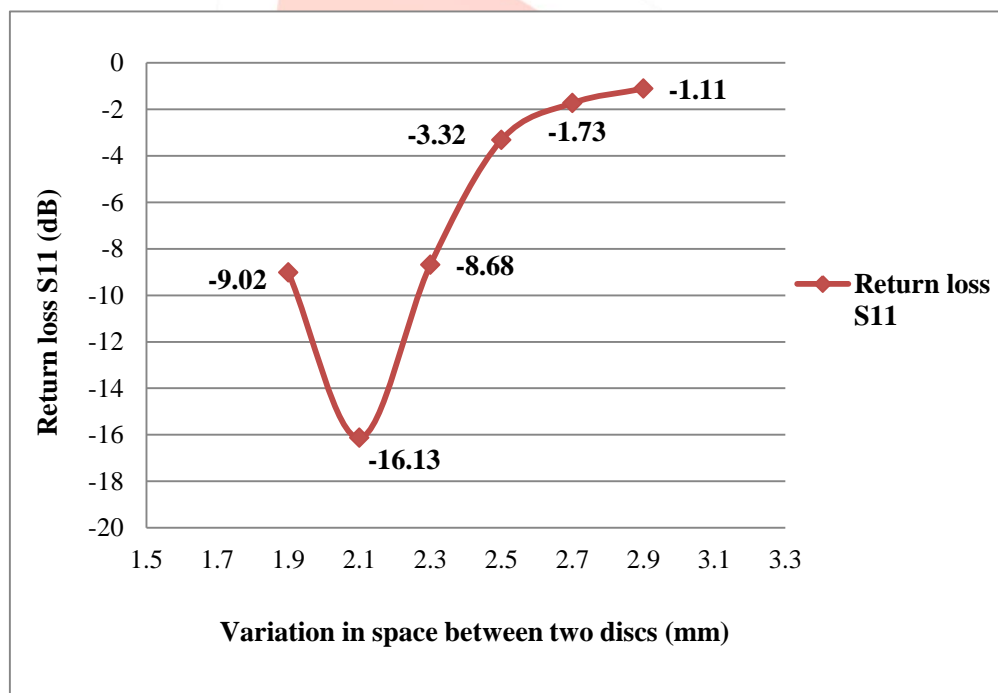
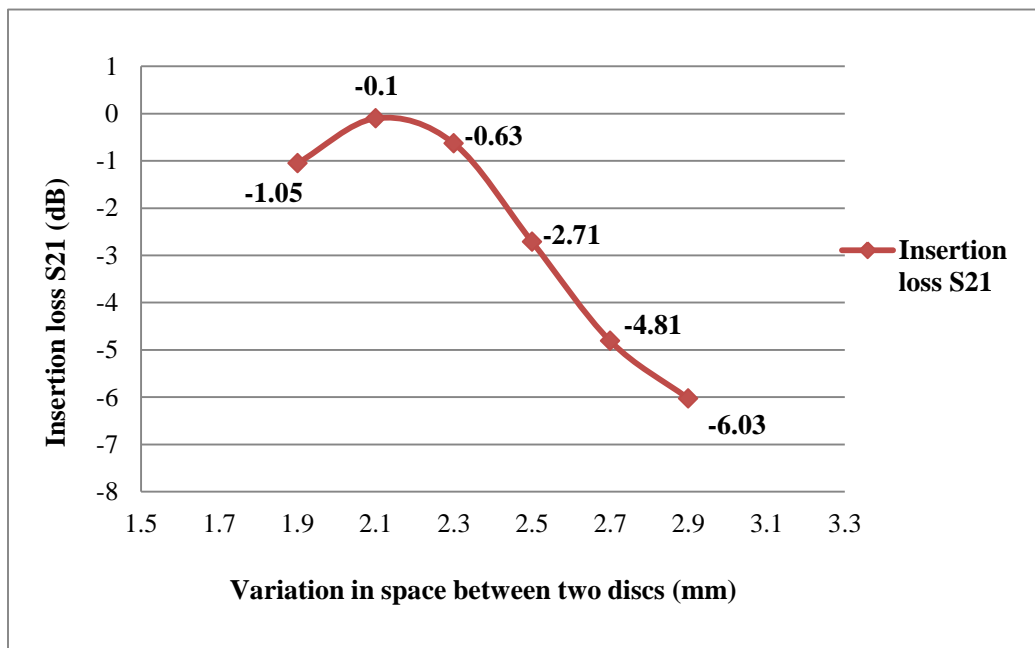Fig. 9 Return loss S11 at variation in spacing **(coolant FC- 75)** between two discs (d = 3.2 mm)

Fig. 10 Insertion loss S21 at variation in spacing (**coolant FC- 75**) between two discs (d = 3.2 mm)

Table 2: Summary of results in HFSS at 42 GHz frequency

Sr No.	Discs thickness (d) (mm)	Optimized thickness of spacing (s) between two discs (mm)	Coolant between two discs	Insertion loss (S21) (dB)	Return loss (S11) (dB)
1	3.2	2.1	FC- 40	-0.01	-25.20
2	3.2	2.1	FC - 75	-0.1	-16.13

In early days, FC-75 has been used for cooling in RF window of Gyrotron. But now a day's FC-40 coolant is used generally due to its good features and benefits. The results shown in Table 2 also show the losses have been also affected by changing the coolant in the RF window. We get minimum losses when using the FC-40 as a coolant for RF window.
 We have also calculated the change in temperature ΔT by passing 200kW for 1sec duration for FC-40 and FC-75 coolants by using equation

$$Q = mC\Delta T$$

Where m is mass of sample, C is specific heat capacity and ΔT is the difference between initial temperature and temperature after 1 sec duration and found it 0.011 °C for FC-40 and 0.11°C for FC-75 which is 10 times greater than FC-40. Hence we have used FC-40 coolant in our design.

V. CONCLUSIONS

In this paper we have shown the design & simulation results of double disc sapphire window for high power 42 GHz Gyrotron in HFSS, and also analyzed losses for variations in disc thickness & variations in spacing between two discs & also compared results for different coolant like FC-40 & FC-75 between two discs. The loss tangent and permittivity of window material affect the absorption and transmission of RF power, but the disc thickness, spacing between discs & different coolant are also important parameters of RF window. For minimum losses in RF window, the ratio of discs thickness & spacing between discs has been optimized using HFSS software.

From above comparisons and results, the minimum Insertion loss (S21) & return loss (S11) have been found -0.01 dB & -25.20 dB respectively for disc thickness 3.2mm, optimized spacing 2.1mm and by using FC-40 coolant between two discs of RF window for 42 GHz Gyrotron.

VI. ACKNOWLEDGMENT

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