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Design of Double Barrier Ceramic Radio Frequency Vacuum Window

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ABSTRACT

Vacuum windows are an essential part of any radio frequency (RF) system which launches/couples RF power from an atmospheric to a vacuum environment. This paper describes the RF design of a double barrier ceramic coaxial vacuum window. Alumina 99.5% pure is considered as ceramic barrier material while inner and outer conductors are oxygen-free copper. As the initial design approach the thickness, slope, depth of ceramic in the conductor is varied and the performance of the window is studied. The design is optimised to achieve the best insertion loss, return loss response for operating frequency range up to 65MHz.

Keywords: Radio frequency; Double barrier; Vacuum window; Insertion loss; Returns loss

1. INTRODUCTION

In radio frequency (RF) systems having their interface with vacuum systems, for example, RF coupler in accelerators or RF launchers for plasma heating, vacuum windows are used to isolate the regions having atmospheric pressure and vacuum. Several Ion Cyclotron Resonance Heating (ICRH) systems in tokamaks worldwide have developed vacuum windows as per their requirement[1-4]. These windows or feed throughs utilise ceramic barriers in a cylindrical or conical shape. The choice of shape and material of the ceramic barrier depends on several factors, for example, ceramic material should have low loss tangent (less than 0.005)[5], better thermal conductivity, minimum strength of electric field (E-field) line components parallel to ceramic surface[4], minimum penetration of E-field lines within the ceramic volume, etc.

The double barrier type vacuum windows are used for enhanced protection against failure of primary vacuum facing barrier, where secondary barrier keeps the vacuum level and protects the chamber from contamination[1-2].

The ion cyclotron heating and current drive (ICH&CD) group at ITER-India is responsible for the development of RF sources for the ITER project[6]. Total 8+1(spare) RF sources will be delivered to coupler 20MW of power to ITER plasma in the frequency range of 36MHz to 60MHz[7]. The ICH&CD group is involved in the development of indigenous transmission line components and test stands of MW level power handling capability[8-9]. As a part of this development program, the ICH&CD group has initiated the development of a coaxial vacuum window for future application in indigenous ITER-like machine. RF Power handling capability of such window will be a few MW for continuous wave (CW) pulse. As the first step of this development program, the design of a prototype double barrier vacuum window with line size 6-1/8inch EIA is initiated. The following paper discusses the RF design of this double barrier vacuum window. Currently, the material selection is aimed to improve the RF characteristics of the window; no thermal properties are taken into consideration.

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2. MODELLING AND SIMULATION

2.1 For Different Inclination of Ceramic Barrier

Initial modelling of double barrier vacuum window was done as shown in Fig. 1 using CST microwave studio (CSTMWS)[10]. The outer conductor (OC) and the inner conductor (IC) were assigned properties of copper (pure) while the ceramic barrier was assigned properties of Alumina (99.5%). This model was simulated for different lengths of ceramic barrier (L) while the thickness of the barrier (10mm) was kept constant.

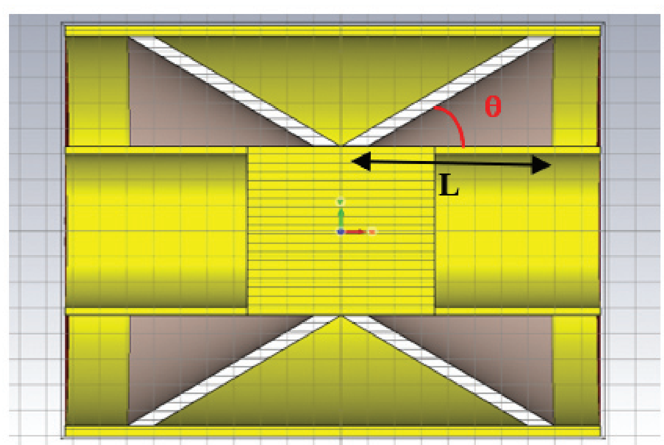


Figure 1. Initial model of double barrier vacuum window.

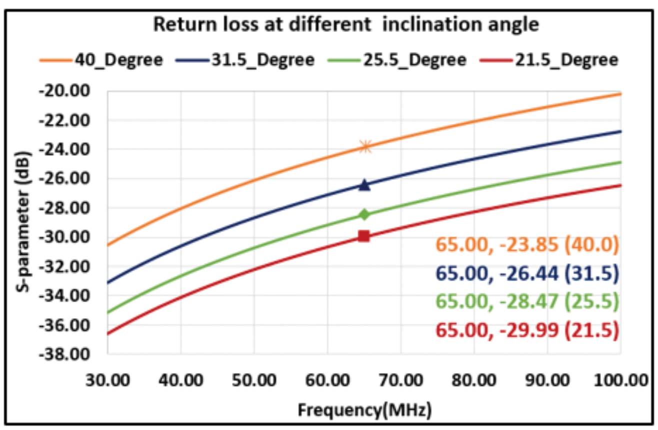
For 6-1/8inch EIA line size the outer diameter (OD) of IC is 66 mm while the inner diameter (ID) of OC is 152 mm, which provides a line impedance of about 50Ω for air or vacuum dielectric between IC and OC from equation 1:

$$Z_0 = \frac{138}{\sqrt{\varepsilon_r}} \log\left(\frac{OD}{ID}\right) \tag{1}$$

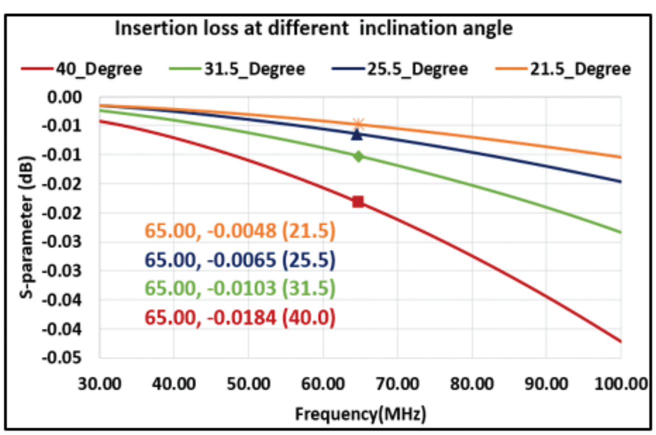
where, Z_0 is line impedance and ε_r is the relative permittivity of the annulus region between IC and OC.

Increasing the length parameter (L) of the barrier decreases its inclination angle (θ) with respect to the inner conductor, at the same time changing the inclination angle varies effective relative permittivity of annulus region at the particular cross-section of the window. This further varies the s-parameter response of the window.

The model was assigned a parametric sweep and the return loss/ insertion loss response was recorded as shown in Fig. 2(a) and Fig. 2(b). It can be observed from Fig. 2(a) that return loss response improves from -23 dB to about -30 dB while "L" is increased from 50 mm to 110 mm i.e. with the reduction in the inclination angle (θ) from 40° to about 21.5°. At the same time, the insertion loss response improves from -0.018 dB to about -0.004dB when "L" is increased from 50 mm to 110 mm as shown in Fig. 2(b).



(a)



(b)

Figure 2. Initial model (a) Return loss (b) Insertion loss.

2.2 Improving Performance by Providing Step in Inner Conductor

After studying the initial response of the ceramic barrier with the inclination angle, it was further tuned by creating a step in the inner conductor with ceramic. The step in the inner conductor is used to improve the characteristic impedance of the window at the location where the two barriers touch the inner conductor as shown in Fig. 3. The width and outer diameter of the step are defined as parameter "W" and "D". A parametric sweep was performed using the above parameters which are as defined in Table 1.

The total length of the window varied from 250 mm to 130 mm for the value of parameter "L" changing from 110 mm to 50 mm. The required length of the window was needed to be no greater than 200mm so the value of "L" chosen for further simulations was 90mm and 70mm. A parametric sweep was performed for above said values of "L" with the other two parameters "W" and "D" as defined in Table 1 and the Return loss/ Insertion loss values were recorded as shown in Figs. 4(a), 4(b) and 4(c).

Figure 4(a) provides return loss response of window for two sets of parametric combination, in first set L and D is kept at values 90mm and 36mm respectively while W is varied from 10 to 30mm, in second set L and D is kept at values 90mm and 46mm while W is varied from 10 to 30 mm. It can be observed

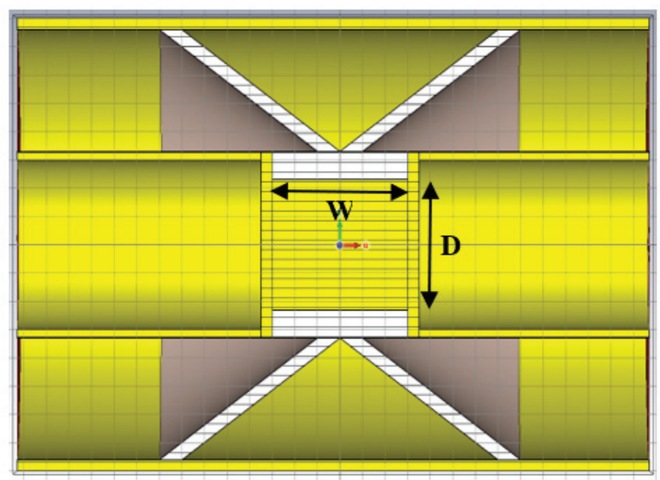
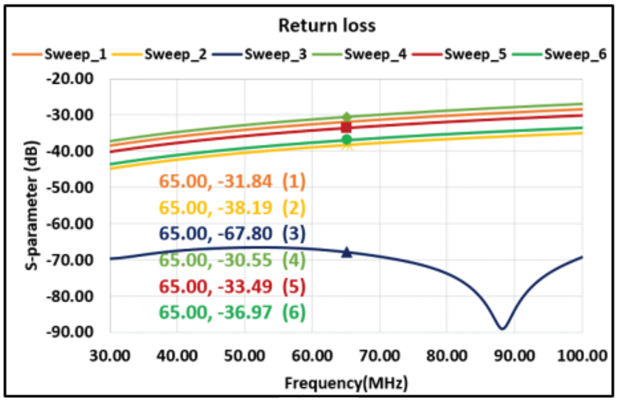


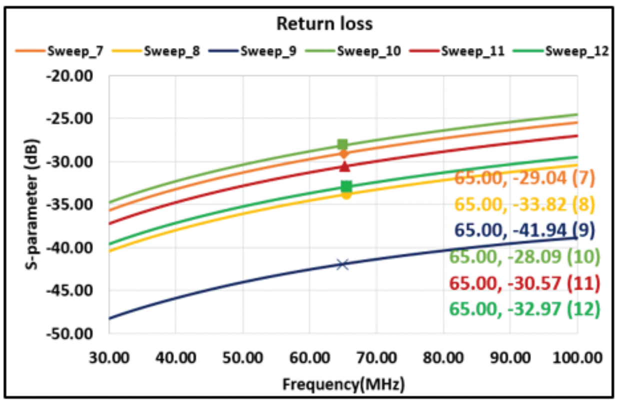
Figure 3. Window with step in inner conductor.

Table 1. Parametric sweep designation

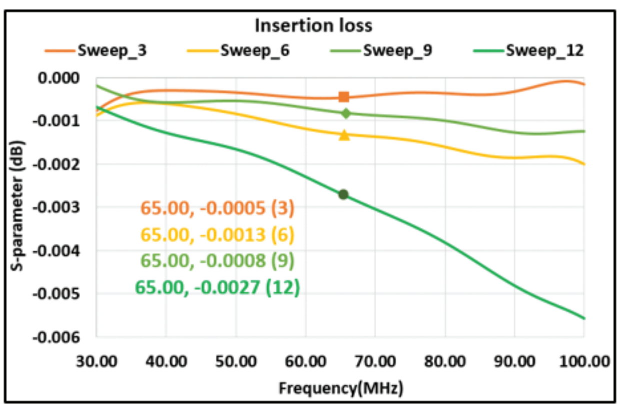
Sweep No.	Parameter		
	L (mm)	W (mm)	D (mm)
1	90	10	36
2	90	20	36
3	90	30	36
4	90	10	46
5	90	20	46
6	90	30	46
7	70	10	36
8	70	20	36
9	70	30	36
10	70	10	46
11	70	20	46
12	70	30	46



(a)



(b)



(c)

Figure 4. Window return loss (a) sweep no. 1 to 6 (b) sweep no. 7 to 12, (c) insertion loss sweep no. 3, 6, 9 and 12.

from Fig. 4(a) that return loss improves for both higher width "W" and smaller diameter "D" of the step.

Thus, the best return loss response is achieved for parametric combination (sweep no. 3) of L, W, and D i.e. 90 mm, 30 mm, and 36 mm respectively, which is -67 dB at 65 MHz. Similarly, Fig. 4(b) provides the best return loss for parametric combination (sweep no. 9) of L, W, and D i.e. 70 mm, 30 mm, and 36mm respectively, which is -41.9 dB at 65 MHz. The insertion loss of the window is better than -0.001dB for both sweep no. 3 and 9 as shown in Fig. 4(c).

Therefore, the best-optimised results for the double barrier type vacuum windows are achieved from sweep no. 3 and sweep no 9.

2.3 Field Distribution Inside Window

The simulation was performed to study the E-field distribution inside the window for a power level of 200kW. As a part of the case study, E-field distribution inside the window for parametric set corresponding to sweep no. 3 and 9 are simulated, Fig. 5 shows the same for sweep no. 9. The maximum E-field strength is 0.35kV/mm and 0.31kV/mm corresponding to sweep no 9 and 3 respectively, at the surface of the inner conductor. Volume loss in the alumina ceramic is 1.56W and 1.14W corresponding to sweep no 9 and 3 respectively. The surface loss over the copper conductor is about 20W. The plot of E-field strength along the surface of the barrier (curve "A to B" shown in Fig. 5) is plotted as shown in Fig. 6. The field strength varies from about 0.08kV/mm for sweep no 9 and 0.06kV/mm for sweep no 3 at point A to 0.04kV/mm at point B. The field strength parallel to the barrier is about 20% of the field strength perpendicular to the inner conductor.

2.4 Window Realistic Model

A realistic model of the window was developed for fabrication utilising parametric dimensions of sweep 3. The simulation was performed to study the E-field distribution inside the window for a power level of 200kW, Fig. 7 shows the same. The maximum E field strength is 0.42kV/mm and volume loss is 1.53W.

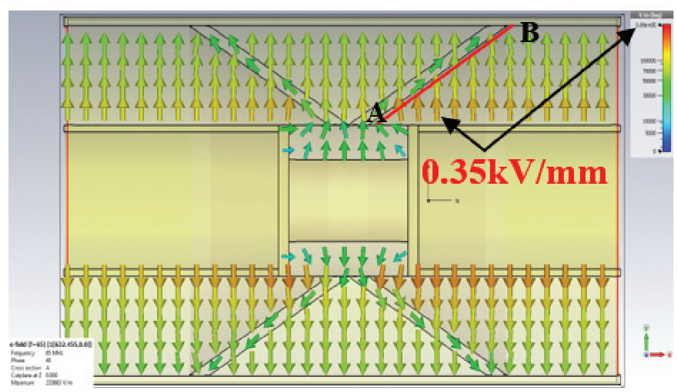


Figure 5. E-field distribution for parameter combination corresponding to sweep no. 9.

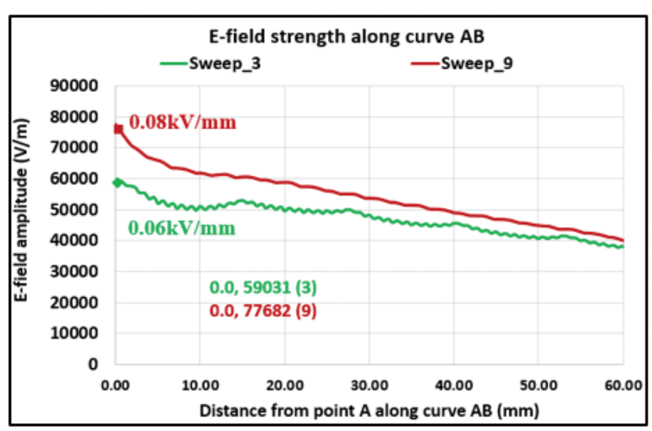


Figure 6. E-field strength parallel to barrier surface for sweep no. 3 and 9.

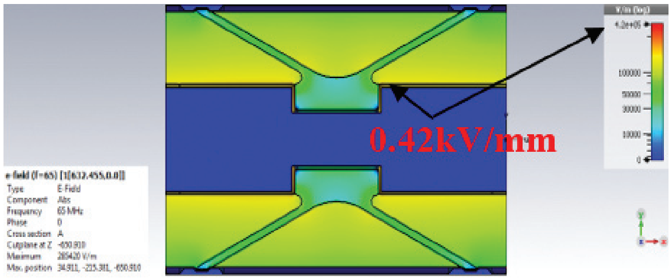


Figure 7. E-field distribution inside window for realistic model.

3. SCOPE

The current paper discusses only the RF design part of the double barrier window. The stresses that occurred during manufacturing and operation affects the performance of the ceramic window. This needs to be studied through finite element solvers. Finally, the window will be manufactured and a high power test will be performed to check voltage stand-off capability and thermal stability.

4. CONCLUSION

RF Design of double barrier type vacuum window is discussed in detail. The initial model was built with two ceramic cones and the angle of inclination was varied to optimise the insertion and return loss. It was observed that the reduction of inclination angle improved the window characteristics. Further modification in the model was performed by introducing a step in the inner conductor. Parametric sweep provided optimised width and diameter of the step for improved return loss and insertion loss response. Sweep no. 3 having a length (L), width (W), and diameter (D) values 90 mm, 30 mm, and 36 mm respectively provided the best return loss and insertion loss response i.e. -67 dB and -0.001 dB at 65 MHz. Finally, field distribution inside the window was simulated at an operating power level of 200kW for both sweep 3 and 9 parameters. The maximum field strength and volume loss in ceramic were about 0.31kV/mm and 1.14W respectively corresponding to sweep 3 parameters and were best-optimised results. Finally, field distribution for a realistic model of the window was carried out which provided maximum field strength of 0.42kV/mm and volume loss of 1.53 W.

The further scope was defined for future fabrication of ceramic window and its RF test.

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In the present paper, he has contributed to the analytical and simulation part.

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