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RF transmission line of a 2.45 GHz ECR ion source

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HIGHLIGHTS

- The TE_{111} mode gets excited in the cylindrical cavity with dimensions of ∅9 cm × 10 cm.
- A four-ridged waveguide is considered for impedance matching and electric field focusing.
- The 9.9 mm quartz pressure window is designed with the lowest return wave loss (S_{11}) of -51 dB.
- The DC break is based on utilizing the insulating rings with low wave return loss of -43 dB.

ABSTRACT

Microwave coupling plays an important role to energize the electrons in an electron cyclotron resonance ion source (ECRIS) plasma. Several components are hired for wave transition from a magnetron to the ECR plasma chamber. In this work, DC break, pressure window, ridged waveguide and plasma chamber have been designed and simulated by COMSOL Multiphysics to transmit the microwave power. The power and frequency are 1 kW and 2.45 GHz, respectively. The results show the TE_{111} mode gets excited and 9.9 mm quartz pressure window maximize the forward transmission power to the cavity. The DC break is based on utilizing the insulating rings along the WR-284 waveguide, which has low wave return loss for a wide range of frequencies. A four-ridged waveguide is considered for impedance matching and electric field focusing. The amplification of the electric field in the middle of cylindrical plasma chamber is satisfied with dimensions of ∅9 cm × 10 cm.

KEYWORDS

ECRIS
RF transmission line
DC break
Pressure window
Ridged waveguide
Plasma chamber

HISTORY

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1 Introduction

ECRIS as the front-end for the most useful applications is hired to produce different ion current in research and medical institute, and industries such as: ion beam etching, ion beam doping, micro-machining and semiconductor fabrication (Jin et al., 2021). For accelerators and ion beam applications that require high-current mono-charge state ion currents, the 2.45 GHz ECRIS has a wide range of applications, due to its advantages of long lifespan, high beam current and good beam quality. This source is based on the resonance, heating and increasing the energy of plasma electrons. For the 2.45 GHz microwave power injection which is equal to the Larmor frequency of rotating electrons around the field lines, the resonance magnetic field is obtained by $B = m_e\omega/q = 875$ G (Geller, 2018). The main parts of this ion source are: RF power supply (magnetron), RF line, plasma chamber, magnet structure and extraction system (Jain et al., 2014). RF line typically consist of directional coupler, circulator, three-stub tuner, DC break, pressure window, ridged waveguide (Chowdhury, 2014). In this work, The RF frequency and power values are chosen of 2.45 GHz and 1 kW, respectively.

2 Research theories

2.1 Plasma chamber

Since the desired resonance frequency in this research is equal to 2.45 GHz, the desired diameter and length for exciting TE_{111} mode in the aluminum cylindrical cavity is about 9 cm and 10 cm, respectively, to produce at least the high electric field of 10^4 V.m^{-1}, Fig. 1. By applying the ridged waveguide, the field in the center of the chamber increases to 1.1×10^5 V.m^{-1}, which is almost twice the case without it (see Fig. 1). Also, the differ-

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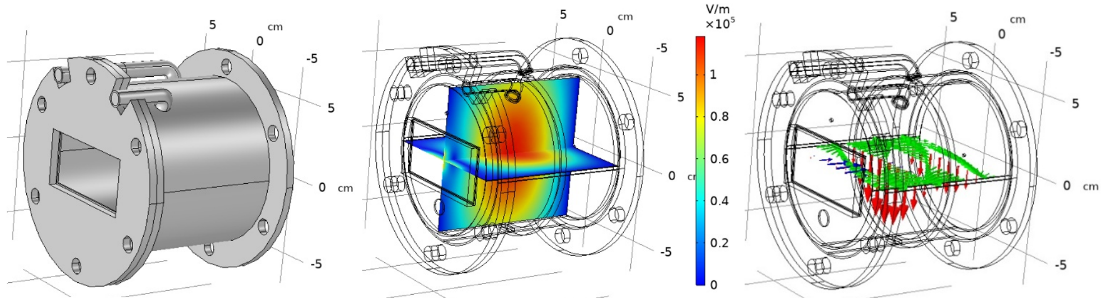

Figure 1: Left) Shematic of simulated plasma chamber, center) the electric field in the plasma chamber due to the presence of the ridged waveguide and right) Direction of electric field (red arrow), magnetic field (green arrow) and power flux (blue arrow).

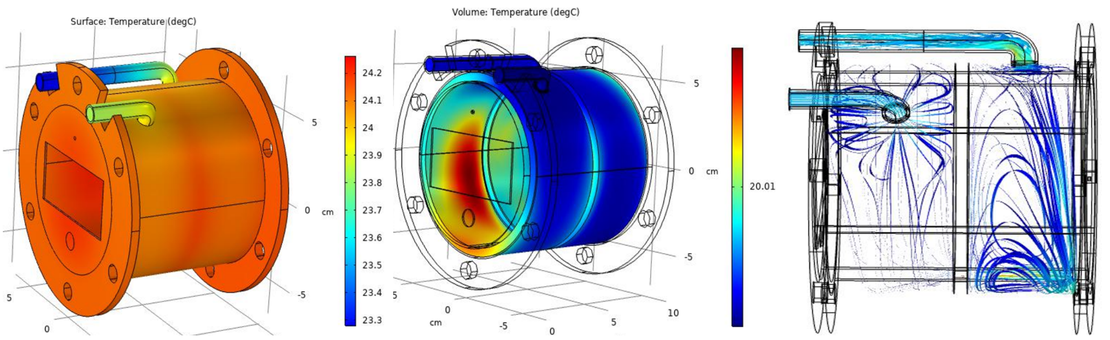

Figure 2: Left) The cavity temperature without cooling, center) cavity with water cooling and right) the water circulating path around the cavity.

ent values of diameter and length can be chosen, but it should be noted that by choosing a large length, the distance between the plasma and the extraction electrode is large and it prevents the extraction of the beam quality. Also, choosing a short length result in a small volume of plasma. Since the inner diameter of the cavity is equal to 9 cm, the remaining space between chamber and coil is assigned to the flanges and the cooling system, which keeps the temperature of the chamber at 20 °C to avoid the volume expansion of the chamber and thus prevent the change of resonance frequency (Fig. 2).

2.2 Ridged waveguide

Coupling of microwave power to the plasma plays an important role to produce a high axial plasma density and improves the output current from the ion source. Since the plasma impedance is equivalent to a complex dynamic quantity whose value changes with the change of various plasma parameters such as magnetic field, gas pressure, incident microwave wave power, etc., so an automatic tuner is also needed. The ridged waveguide is designed by considering the standard waveguide WR-284 with dimensions of 7.2136 cm and 3.4036 cm, which matches the impedance of the waveguide with the plasma impedance (around 50-150 Ω). These waveguides are usually used for: 1- optimizing the coupling between the microwave wave source and the plasma chamber and 2- Focusing the electric field on the central axis of the chamber. The schematic of a four-step ridged waveguide is shown in Fig. 3

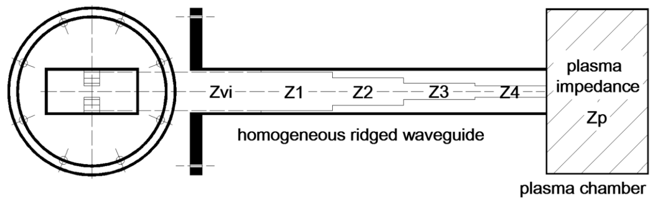

Figure 3: Schematic of the ridged waveguide with four steps coupled to the plasma chamber.

In this figure, Z_1, Z_2, Z_3, and Z_4 are the impedances of each step of the waveguide, Z_{vi} is the wave impedance (or voltage-current impedance) of the standard WR-284 waveguide, and Z_p is the plasma impedance [5]. The wave impedance of the standard waveguide is obtained from Eq. (1):

$$Z_{vi} = \frac{2b\pi\eta}{2a}\Big[1 - (\frac{\lambda_0}{\lambda_c})^2\Big]^{-\frac{1}{2}} \tag{1}$$

where η, b, a, λ_0 and λ_c are the impedance of free space (377 Ω), the height and width of the waveguide, the free space wavelength and cutoff wavelength, respectively. As a result, the value of wave impedance for standard rectangular waveguide WR-284 in TE_{10} mode and frequency of 2.45 GHz is equal to 527 Ω. The length of each step is equal to a quarter of the wavelength at the working frequency of 2.45 GHz, and the impedance of each part of the ridged waveguide is determined by the Eq. (2) (Pozar, 2021):

$$\frac{Z_{n+1}}{Z_n} = \exp\Big[2^{-N} C_n^N \ln\frac{Z_n}{Z_0}\Big] \tag{2}$$

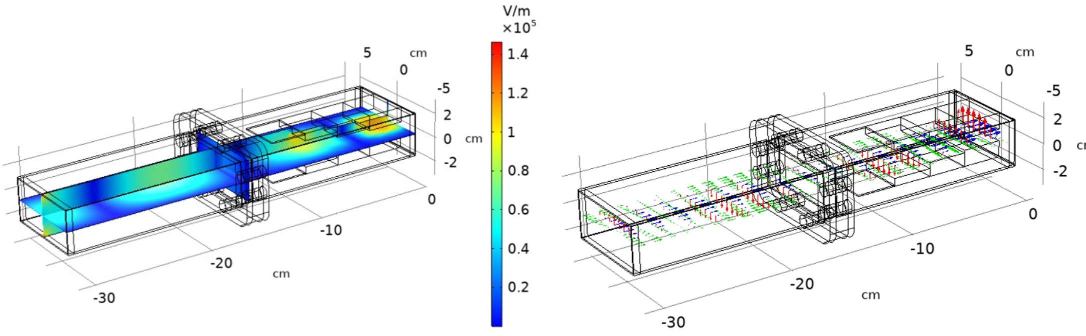

Figure 4: Left) The electric field released in the system with the presence of the vacuum window, and right) electric, magnetic fields and electric power density released with the presence of vacuum window.

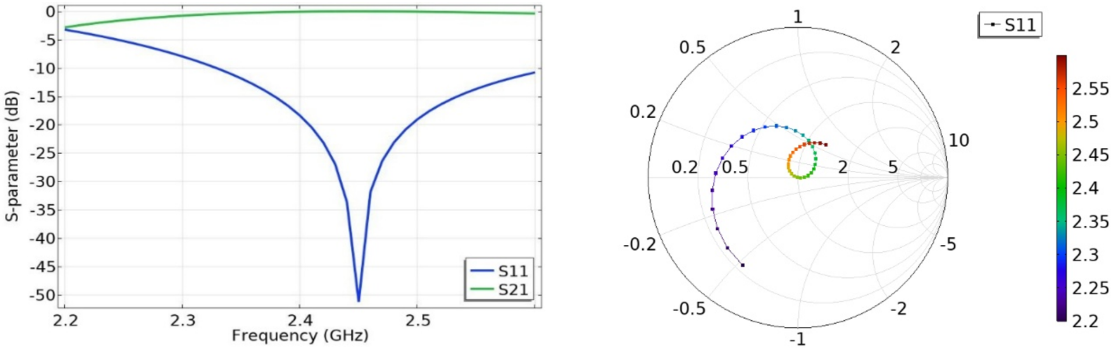

Figure 5: Left) Variations of wave return loss (S_{11}) and transmission loss (S_{21}) of a quartz window with as a function of thickness of 9.9 mm and right) Polar display of return wave loss (S_{11}) as a function of frequency.

Here n and N are the number of steps, the total number of steps. The determined values for the impedance and the distance between the ridges in each step of the waveguide are shown in Table 1. The designed four-step ridged waveguide is shown in Fig. 6.

2.3 Pressure window

The microwave vacuum or pressure window is widely used to keep the vacuum (Fig. 4-left). The thickness of the window should transmit the wave power and stop the energetic electrons towards the wave transmission line and magnetron. In this work, a single-layer quartz window which is cheap and available, was designed. The thickness of the window was checked from 1 to 20 mm and the lowest return wave loss (S_{11}) was observed for thickness of 9.9 mm. Figure 5 shows the value of S_{11} for 2.45 GHz is equal to -51 dB, and the transmission loss (S_{21}) is equal to 0.01 dB for 9.9 mm pressure window.

Table 1: Impedance values and the distance between the ridges in each step of the waveguide.

Number	Distance (cm)	Impedance (Ω)
1	3.2	475.1
2	2.2	313.7
3	1.3	168.3
4	0.9	111.2

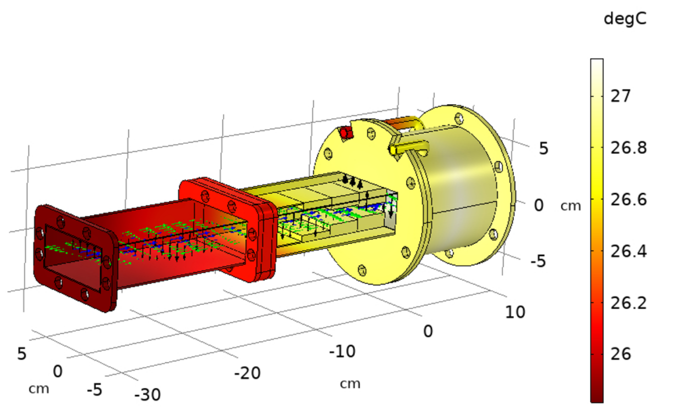

Figure 6: Temperature distribution and electric field (black arrow), magnetic field (green arrow) and electric power density (blue arrow) in the system with the presence of vacuum window.

As it can be seen in Fig. 6, the temperature of the chamber increases to about 27 °C. In this figure, the green arrows represent the magnetic field and the blue arrows represent the electric field.

2.4 DC break

DC break or high voltage break is required to isolate the RF generator (magnetron) from the high voltage applied to the plasma chamber (50 kV in this design). So, mechanical strength and low wave loss are the important features that should be considered. Teflon, high density polyethy-

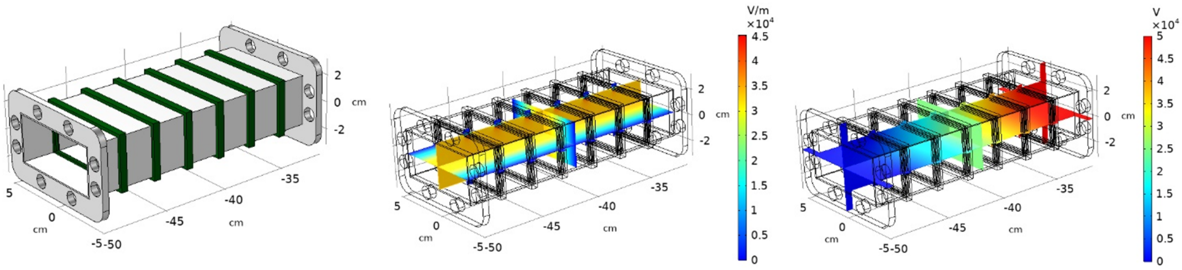

Figure 7: Left) Schematic of DC break using G-10CR resin, center) variation of electric field and right) variation of electric potential.

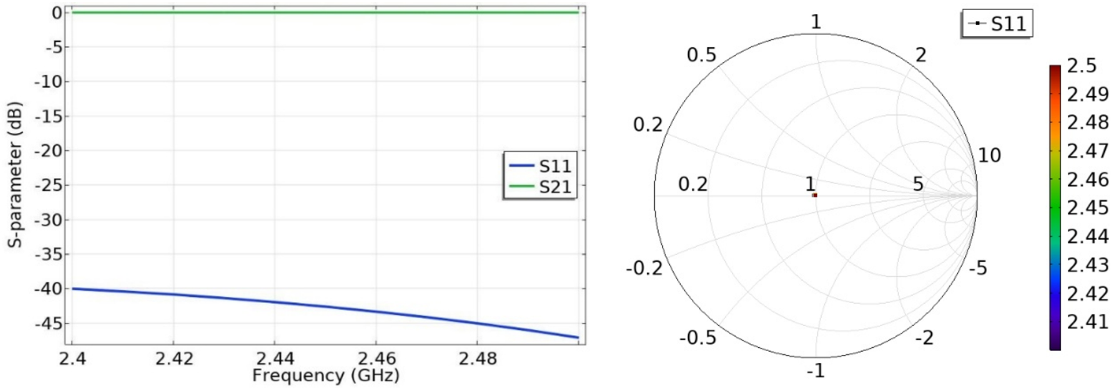

Figure 8: Left) Changes of wave return loss (S_{11}) and transmission loss (S_{21}) of the DC break and right) Polar display of return wave loss (S_{11}) as a function of frequency.

lene, and polypropylene are the most widely used materials for this purpose. As described in Ref. (Asadi Aghbolaghi et al., 2023), by considering 6 insulating washers (or rings) such as G-10CR resin with a thickness of 5 mm (in the waveguide connection with thickness of 2 mm) are placed in the path of the waveguide. Also, the width of each piece of waveguide is equal to 2.5 cm. Figure 7 shows how the transmission and return loss changes for the DC break. As seen, at the frequency of 2.45 GHz, the value of S_{11} is equal to -43 dB. Since the high voltage break is not placed in front of the wave, all the investigated frequencies pass through the center of the Smith-Chart (Fig. 8) with little loss.

3 Conclusions

In this work, DC break, pressure window, ridged waveguide and plasma chamber have been designed and simulated by COMSOL Multiphysics to transmit the microwave power. The results show the 9.9 mm quartz pressure window maximize the forward transmission power to the cavity. The DC break is based on utilizing the insulating rings along the WR-284 waveguide, which has low wave return loss for a wide range of frequencies. A four-ridged waveguide is considered for impedance matching and electric field focusing. The amplification of the electric field in the middle of cylindrical plasma chamber is satisfied with dimensions of $\emptyset$9 cm $\times$ 10 cm.

Conflict of Interest

The authors declare no potential conflict of interest regarding the publication of this work.

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