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DESIGN OF MINIATURE WAVEGUIDES AND DIAMOND WINDOW ASSEMBLY FOR RF EXTRACTION AND VACUUM ISOLATION FOR THE CWA *

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Abstract

This paper outlines the design of a diamond vacuum window and a millimeter wavelength (mmWave) waveguide assembly that will hold vacuum but still allow the mmWaves to propagate out of the structure for diagnosis and thermal management purposes. Currently under development at Argonne is a corrugated wakefield accelerator (CWA) that will operate at mmWave frequencies, with its fundamental mode of operation at 180 GHz and relatively high power levels up to 600 W. The fundamental mode needs to be extracted from the accelerator at approximately every 0.5 m to prevent the unwanted heating of the accelerator structure. Therefore, the structure is intentionally designed so this fundamental mode does not propagate further; instead it is transmitted through the waveguide assembly under vacuum and out via the vacuum window. As a result of the relatively high mmWave power densities, CVD diamond was chosen as the vacuum window material due to its low electromagnetic losses, mechanical strength, and superior thermophysical properties. Mechanically it is necessary to be able to hold the tight tolerances necessary for window performance at millimeter wavelengths. Other mechanical difficulties involve assembly of the window due to the CVD diamond material and preservation of ultra-high vacuum even if the integrity of the CVD diamond window is somehow compromised.

INTRODUCTION

Under development at Argonne National Laboratory (ANL) is a miniature accelerator that utilizes Čerenkov radiation to generate an accelerating electromagnetic (EM) mode at 180 GHz. The structure facilitates this Čerenkov radiation due to its corrugated waveguide structure and high-charge electron bunches [1]. After the accelerating structure ends, it is necessary to extract this accelerating mode using a fundamental coupler. This coupler is designed to couple only to the accelerating mode and transport it out of the main section via four rectangular waveguides. These waveguides then transport the mode out via the vacuum windows to RF loads. The fundamental coupler is shown in Fig. 1, along with a portion of the accelerating structure.

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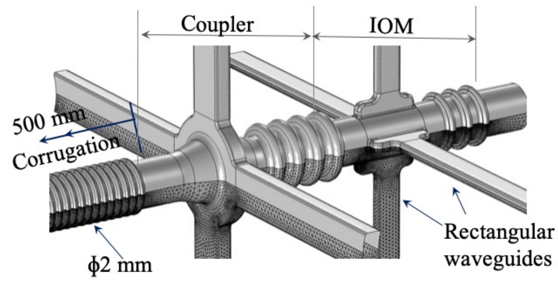

Figure 1: The corrugated waveguide and fundamental coupler followed by the IOM.

First and foremost, the vacuum window must perform adequately electromagnetically, with minimal losses and reflection of the extracted electromagnetic (EM) wave, thereby maximizing transmission out of the structure via the window. Any reflection off the window or its structure could return to the accelerator and disrupt its operation, potentially heating or, even worse, destabilizing the beam. Minimizing EM losses is vital since it is necessary to transport as much of the wave's energy as possible to a location outside of the accelerator vacuum where it can be properly cooled. The main basis of the design is the window material; specifically, chemical vapor deposition (CVD) diamond was chosen for its thermal and electrical properties. Currently CVD diamond windows are used extensively in mmWave gyrotrons operating at megawatt power levels [2, 3].

It is also necessary to keep in mind that this accelerator is operating at a much shorter wavelength than a typical accelerator, these mmWaves having a freespace wavelength of 1.7 mm at 180 GHz. Thus, all the design parameters that are on the EM side must have submillimeter tolerances to ensure EM performance. There are additional issues relating to machining finishes.

As mentioned previously, the outputs of the fundamental coupler are rectangular waveguides but for structural and vacuum reasons, windows at these frequencies are typically circular. A rectangular window is not as structurally strong and is more difficult to fabricate, more difficult to braze, and more prone to vacuum leaks in the corners. Thus, it is necessary to transition from a rectangular waveguide to a circular one, and then uptaper to a larger diameter waveguide. A larger diameter window is preferable for heating concerns along with ease of manufacturing and assembly, though it introduces more potentially disruptive resonances within the window itself.

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This design employees a double-window structure to protect the accelerator from a catastrophic failure of one of the windows. Even though a window failure will still bring the system offline, having a second window will allow the system to maintain its vacuum levels and prevent contamination. The system would be brought offline since a damaged window would have extremely poor EM performance and result in poor transmission and high levels of reflected power.

Thus, the design consists of a rectangular-to-circular waveguide transition section leading to a circular waveguide with two mounted circular diamond windows in series. The rectangular waveguide is connected to one of the fundamental coupler's rectangular waveguide arms, which is under vacuum. The other side of the window section is at atmosphere, either radiating into a load via free-space or directly into a waveguide load. Figure 2 shows the entire window structure.

FABRICATION CONCERNS AT mmWAVE FREQUENCIES

Two major fabrication concerns at these frequencies are surface roughness and dimensional accuracy. Poor surface roughness results in increased ohmic losses; this is due to the effect of the skin depth of EM waves. The skin depth is how deeply the wall currents of the EM wave mode penetrate into the conductor. It is inversely dependent on the conductivity and magnetic permeability of the material but, most importantly, inversely proportional to the operating frequency. Thus, the higher the frequency, the smaller the skin depth and the greater the need for reduced surface roughness. Having the surface roughness greater than the skin depth at the operating frequency causes discontinuities in the conductor of the wall currents, effectively increasing the ohmic wall losses. The surface roughness referred to is the roughness average (R_a) of a surface. At 180 GHz, with annealed copper's conductivity of $5.8{\times}10^7$ S/m , the skin depth is 155 nm. Ideally the skin depth should be a number of times higher than the surface roughness [4].

Regarding dimensional accuracy, at 180 GHz the wavelength is 1.66 mm. Thus, a variance of ±50 µm would result in a frequency deviation of ±5 GHz in vacuum, while it would be even greater within the diamond window material due to its relative permittivity value. Potential effects on EM performance due to dimensional variance on window performance is discussed in a later section alongside a tolerance study done in simulation.

WAVEGUIDE AND WINDOW STRUCTURE

Rectangular-to-Circular Transition

The element consists of a transition from a standard rectangular WR5.1 waveguide to a circular waveguide of 1.5-mm radius. A smooth taper is necessary to provide good mode conversion from the rectangular fundamental waveguide mode (TE_{10}) to the circular fundamental waveguide mode (TE_{11}); ideally all the EM energy is converted from

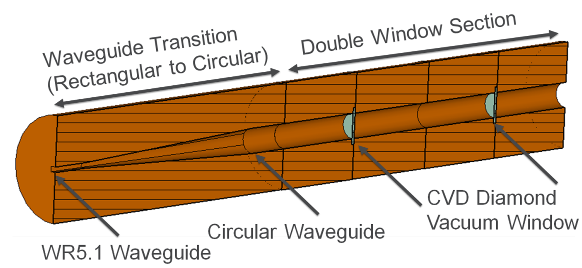

Figure 2: The entire window structure is shown. On the left is the rectangular-to-circular transition. In the center is the diamond window section, with the two windows shown.

one mode to the other. An abrupt or poorly fabricated taper would lead to reflections and, potentially, mode conversion to undesirable waveguide modes. Converting to modes other than the desired circular TE_{11} mode would significantly reduce the EM performance of the structure and increase reflections and conductive losses.

The length of the uptaper is 32 mm, with 5 mm of straight WR5.1 and 5 mm of straight circular waveguide on either side. It is necessary to have at least a few wavelengths on either end of the taper to ensure the mode is stable before any attempt is made to add a bend, window, or other transition, otherwise there is a risk of mode conversion or reflections.

Window Materials

The material properties of various materials traditionally used for RF vacuum windows are listed in Table 1. Note the far superior thermal conductivity of CVD diamond and lower loss tangent. The higher the relative permittivity, the thicker the window design, since the window is typically an integer number of the half wavelength within the window.

Table 1: Typical RF Vacuum Window Material Properties

Material	Relative Permittivity	Loss Tangent	Thermal Conductivity W/(m K)
Diamond	5.68	$2{\times}10^{-5}$	2000
Alumina	9.9	0.001	30
BeO	6.5	0.004	330
Quartz	3.75	0.0004	5

Diamond Window

The window's thickness is determined by the EM wavelength at the operating frequency of 180 GHz within the material, dependent on its relative permittivity (ε), 5.68 for CVD diamond. The ideal thickness is an integer of the half wavelength, which at 180 GHz is 0.35 mm. A thicker window would function equally well in reflection performance but would result in greater transmission losses within the window itself due to the longer signal path length.

The design choice of the maximum diameter of the circular waveguide is constrained by the need to transition from

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Table 2: Tolerance analysis of the CVD diamond window's thickness and radius with the resulting insertion loss (S_{21}) (dB) at 180 GHz. In bold is the nominal insertion loss value.

	S_{21} (dB) 180 GHz	Window Thickness -50 µm	0.35 mm	+50 µm
Radius	-50 µm	-0.70	-0.090	-0.64
	2.2 mm	-0.90	**-0.015**	-0.66
	+50 µm	-0.815	-0.014	-0.77

a rectangular waveguide to a circular one. A larger diameter waveguide would be preferable, since it would result in a larger diameter window that would be easier to fabricate and mount, and have improved thermal handling. However, a larger diameter window could also potentially have more resonance modes within, and would also require a longer transition piece to ensure adequate EM performance. A longer transition piece would be more difficult to fabricate and would increase costs.

The double-window design presents the potential issue of a standing wave developing between the two windows if they are not spaced apart adequately. This standing wave is generated and trapped by reflections off the windows. If a standing wave were to build up, it would cause an EM wave mismatch in the window structure, resulting in further reflections back to the accelerator structure. Additionally, this standing mode would introduce further thermal losses in the structure. This risk is mitigated by the spacing between the windows being at least a few wavelengths, chosen here as 24 mm, so any trapped standing waves would be attenuated away. The overall length of the double window section is 54 mm, bringing the total length of the structure to 86 mm.

SIMULATION RESULTS

The entire design (shown in Fig. 2) was simulated in CST Microwave Studio in the frequency domain, with the scattering parameter results shown in Fig. 3. At the mode of operation, 180 GHz, the insertion loss (S_{21}) is −0.015 dB, which is the amount of signal that is not transmitted thru the structure, either from conductive losses or reflection back. The return loss (S_{11}), the amount of signal reflected back to the fundamental mode, is −25 dB, and the passband is 7.5 GHz. This design allows a substantial frequency deviation from the designed frequency of 180 GHz. Note that this passband has two sharp dips on either end. These are resonance modes that occur within the diamond window and are a function of the window's material properties, thickness, and radius. These resonance modes are unavoidable and can only be shifted up or down in frequency by changing the thickness or radius of the window. During the design process these parameters were chosen to provide a large enough passband between resonances and ideally place the mode of operation in the center of the passband.

A tolerance analysis was done of a single CVD diamond window and compared to the design parameters, as shown in Table 2. The major degradation in performance was due to

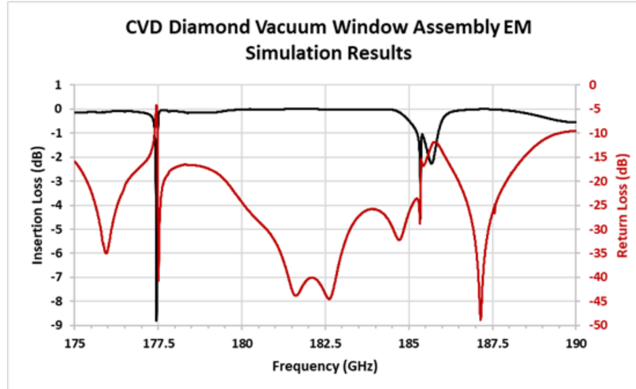

Figure 3: Electromagnetic simulation results from CST Microwave Studio of the entire vacuum window assembly, as shown in Fig. 2.

the window thickness being out of specification. Simulations show that a ±50 µm difference in thickness increases the transmission loss (S_{21}) at 180 GHz by 0.55 dB and 0.89 dB, respectively. Since ±50 µm would be equivalent to a half wavelength at 207 and 177 GHz, respectively, the degradation in performance with respect to a variance in the window's radius was not significant.

As a result of this analysis, when the windows are delivered and before they are inserted into the assembly, they will be characterized electromagnetically using a vector network analyzer (VNA) to determine if their EM performance will suffice at 180 GHz. A window that is at the upper or lower bounds of the tolerance would be identified via the EM measurements and rejected for use in the vacuum window system.

SUMMARY

An EM design at these millimeter wavelengths presents numerous issues from a fabrication and assembly standpoint. Issues such as surface roughness and dimensional tolerances are crucial for adequate EM performance. The window system presented focuses on a simple design to minimize these difficulties. The selection of CVD diamond as the window material is based on its electrical properties, low loss, and low relative permittivity, along with its superior thermal properties compared to other traditional vacuum window materials. The choice to use a circular window presents the need for a rectangular-to-circular waveguide transition, though this trade-off allows for a more mechanically robust circular window. Finally, a double-window design introduces a safety redundancy such that if one window fails, the vacuum of the entire accelerator is not compromised.

FUTURE WORK

With the EM design complete, the mechanical and vacuum design and sourcing of parts are the next steps. Once the parts have been fabricated, EM testing of the windows, the elements of the structure, and the fully assembled structure will be done using the new mmWave test lab at Argonne.

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Finally, assembly and vacuum testing will be done at ANL before the window system is deployed on ANL's corrugated wakefield accelerator.

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