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A VACUUM WINDOW FOR A 1 MW CW 110 GHz GYROTRON

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Abstract

Development of high power microwave sources for fusion applications is limited by the availability of suitable vacuum windows in the 100 to 200 GHz frequency range. A novel vacuum window is described which uses water cooled sapphire as the dielectric. Heat removal is achieved by using thin slats of sapphire interleaved and brazed to niobium hexagonal tubes in which the cooling water flows. Analysis indicates a window 100 cm^2 in area can readily pass 1 MW in the HE_{11} mode at 110 GHz for current experimental applications and 1 MW with a HE_{11}^{0}–HE_{12}^{0} mixture at 170 GHz, the projected ITER frequency.

Analysis of the Window

A typical cross-section of the window is shown in Fig. 1. The incident power is assumed to be linearly polarized with the electric field perpendicular to the slats as shown. As long as the period $h < \lambda$, where λ is the free space wavelength, there are no higher propagating modes excited by the structure with normal incidence.

With the indicated polarization, the tapered surfaces in Fig. 1 act as E-plane tapers, and can be analyzed as if they were part of a fundamental waveguide. From such an analysis [1] we find that the taper need only be 1.5 λ long for our h/h' ratio to make the reflected power $< 1 \times 10^{-3}$ of the incident power. The the dielectric barrier is assumed to have a resonant thickness ℓ; that is, $\ell = N\lambda_\epsilon/2$, where the guide wavelength $\lambda_\epsilon = \lambda/\epsilon^{1/2}$ to a very good approximation since the waveguide width $a \gg \lambda$, and where N is an integer. We chose $N = 6$ for our 110 GHz window to provide adequate mechanical strength.

Although reflections will be neglegible at the design frequency, both dielectric loss and ohmic loss, especially ohmic loss under the dielectric, are significant. The loss tangent of sapphire is well documented [2] and acceptably low, as shown below. Regarding the resistivity at the sapphire-metal interface, we have done considerable development work to achieve a braze to sapphire that is entirely free of voids at the sapphire surface and has low resistivity. We are presently able to produce a void free braze that has a loss close to that of molybdenum, as seen from Q measurements of a 60 GHz TE_{01} mode cavity in which a sapphire disk braze sample is compared with a sapphire disk backed by reference metal disks. Although the dc resistivity of molybdenum is 5.7×10^{-8} Ω-m, we do not know the effective value at 110 GHz. Typically the ratio of microwave to dc resistivity is largest for the best conductors, and approaches 1 for the poorest ones. In our calculations, we have assumed an effective resistivity ρ of 10×10^{-8} Ω-m, unless otherwise indicated. We have assumed the same ρ for the taper surfaces, which have gold evaporated onto the rough (Electric Discharge Machine finish) surface of the niobium structure.

The various losses are important not only with regard to loss of power, but with regard to heat removal. The expressions for insertion loss and heat flux, which include the effect of a standing wave in the sapphire, are given in Table 1. In addition, the table gives predicted values for the heat flux into the water channel, and the peak temperature in the sapphire, for the indicated peak incident power P_0. 40 kW/cm^2 corresponds to 1 MW in the HE_{11} mode incident on a window of 100 cm^2 area, while the reduction to 30 kW/cm^2 peak can be achieved by a 1.5% HE_{12}^{0}–98.5% HE_{11}^{0} mixture. The values of $\tan\delta$ in the table correspond to temperatures $\geqslant$ than the calculated temperatures, and are therefore conservative. Table 1 also shows predictions for a 170 GHz window($h = 1.73$ mm, $h' = 0.69$ mm, $w = 0.56$ mm, $\ell = 2.3$ mm) for two values of P_0. A finite element analysis shows that, for the 110 GHz and lower P_0 170 GHz cases, the maximum stress, which occurs in the sapphire, is < 83 MPa, which is well within acceptable stress limits.

Experimental Results

Two structures of the cross-section of Fig. 1 have been built and tested at low power. The first was made of aluminum alloy, without sapphire, to verify the low mode conversion and ohmic loss. The second is a complete window with a 6 cm × 6 cm aperture. The expected ohmic loss of the aluminum frame is 1.0%, assuming a resistivity $\rho = 10 \times 10^{-8}$ Ω-m, while the measured loss for the HE_{11} mode is 1% ± 1%, the uncertainty coming from ripple due to trapped spurius modes. The estimated combined dielectric and ohmic loss ranges from 3.4% to 4.5%, for assumed $10 \times 10^{-8} \leqslant \rho \leqslant 20 \times 10^{-8}$ Ω-m. The measured loss is 4% ± 2%, which shows the loss estimates are roughly correct.

As of this writing, no high power tests have been performed, but they are anticipated shortly.

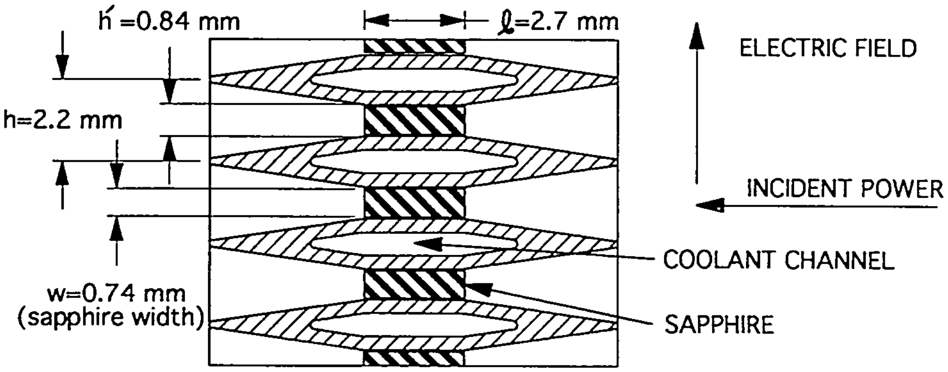

FIG. 1. Typical cross-section of 110 GHz distributed window.

Table 1: Summary of Window Calculations

	Formula Used	HE_{11} Profile $P_0 = 40$ kW/cm^2 110 GHz	HE_{11} Profile $P_0 = 40$ kW/cm^2 170 GHz	Flattened HE_{11} $P_0 = 30$ kW/cm^2 170 GHz
Peak ohmic heat flux at metallization, W/cm^2	$P_0\,(h/w)(1+\epsilon')$ $\times\ (R'/377)$	368 $(R' = 0.104)$	441 $(R' = 0.130)$	331 $(R' = 0.130)$
Peak heat flux from dielectric loss, W/cm^2	$P_0\,(h\omega/2\,c)(1+\epsilon')$ $\times\ \tan\delta$	134 Peak $T = 122$ °C $(\tan\delta = 2.6{\times}10^{-4})$	327 $(\tan\delta = 5.1{\times}10^{-4})$	194 Peak $T = 105$ °C $(\tan\delta = 4.0{\times}10^{-4})$
Insertion loss at metallization	$(2\,\ell/w)(1+\epsilon')$ $\times\ (R'/377)$	2.1% $(\ell = 2.7$ mm$)$ $(R' = 0.104)$	2.9% $(\ell = 2.3$ mm$)$ $(R' = 0.130)$	2.9% $(\ell = 2.3$ mm$)$ $(R' = 0.130)$
Insertion loss in dielectric	$(\ell/2)(\omega/c)(1+\epsilon')$ $\times\ \tan\delta$	0.80% $(\tan\delta = 2.6{\times}10^{-4})$	2.2% $(\tan\delta = 5.1{\times}10^{-4})$	1.7% $(\tan\delta = 4.0{\times}10^{-4})$
Insertion loss in tapers	$[8\,d/(h-h')](R'/377)$ $\times\ln(h/h')$	0.66% $(R' = 0.104)$	0.86% $(R' = 0.130)$	0.86% $(R' = 0.130)$

R' (surface resistance) $= (2\,\mu_0\omega\rho)^{1/2}/4$

ϵ': real part of sapphire dielectric constant

P_0: peak incident microwave power at window

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References

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[2] G. Link and R. Heidinger, Conference Digest, 18th Int. Conf. on Infrared and Millimeter Waves 1993, Colchester, p. 150-151.