DESIGN OF A HIGH AVERAGE POWER WAVEGUIDE WINDOW

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Abstract

A study has been performed to design a waveguide vacuum window capable of propagating >1 MW average power operating at 500 MHz. This would extend current technology by about a factor of 2 in average power for stand-alone windows, made possible by advances in available ceramic size and quality. The work to be presented comprises of RF design and corresponding thermo-mechanical analysis.

1 INTRODUCTION

A facet common to many current and proposed accelerator projects is extremely high luminosity, demanding ever increasing beam current, one consequence of which is the need to transfer high average power to the beam. One component in the chain of power transfer is an RF vacuum window.

For frequencies around 500 MHz, at least two rectangular waveguide window designs have been successfully tested at 500 kWCW. One is manufactured by Thomson Tubes for the CESR III upgrade [1] and the other is an in-house design for the PEP-II B Factory [2]. Cornell's testing of the Thomson window indicates that it has the potential to operate at the 1 MWCW level from a thermal point of view if the Titanium anti-multipactor coating on the ceramic is sufficiently thin. But this comes at the expense of lengthy RF conditioning and greater potential of troublesome operation when attached to an accelerator cavity. A coaxial window designed by KEK for their B Factory has been tested at 850 kWCW [3], which certainly exceeds expectations for a coaxial geometry.

Factors that limit RF window performance are: 1) heating of the vacuum barrier (ceramic), 2) multipactor discharge, and 3) violent arcing. High average-power windows are most susceptible to the first two items. Multipactor discharge is a precarious phenomenon, and in the end usually addressed by applying a sufficiently thick anti-multipactor coating, such as Titanium or Titanium Nitride, to trouble spots. This coating, though, is RF lossy and contributes to the other problem encountered in high average-power windows, heating of the ceramic.

In addition to surface heating by the anti-multipactor coating, bulk heating of the ceramic occurs due to its non-zero dielectric loss tangent. Typically, the perimeter of the ceramic disk is held at a fixed temperature by a cooling water interface, and the thermal gradient of the disk interior induces mechanical stress which will cause fracture of the ceramic at sufficiently high gradient.

It is mainly the problem of heating of the ceramic and induced mechanical stress which will be addressed in this paper. In Section 2 is the RF design of two types of windows, in Section 3 thermo-mechanical analyses corresponding to the RF designs, and in Section 4 comparison of designs.

2 RF DESIGN

A survey was taken among ceramic manufacturers to determine what sizes, shapes, and materials are readily available with low dielectric loss tangent ($\delta \sim 10^{-4}$). Besides the well-known Alumina, plates of low-loss Beryllia may be available in sizes up to 18" x 9" x 1/2" [4]. Beryllia is an attractive choice since it has a high thermal conductivity, resulting in lower thermal gradients, although the material has a lower tensile strength than Alumina. Thus, the two ceramics considered here are Alumina and Beryllia.

The 3D computer code MAFIA with its *s*-parameter macro was used for RF designs. A satisfactory degree of confidence exists in MAFIA's accuracy given comparisons of computations to measurements performed on Cornell's Thomson window. Ultimate fine tuning of a prototype, though, will always be in order.

Two different waveguide window geometries were considered. The first type utilizes posts in the waveguide to compensate the mismatch of the ceramic vacuum barrier and the second is a self-matched design.

2.1 Tuning-Post Matching

The geometry of a quarter section of a tuning-post matched window is shown in Fig. 1. For such a window, MAFIA is first used to generate curves of scattering parameters (mainly $s11$) of only the symmetric pair of tuning posts in waveguide, where the RF reference plane is at the center of the posts. Sample curves are shown in Fig. 2. Next, MAFIA is used to determine the scattering parameters of only the ceramic disk embedded in the metal frame in waveguide, again with the RF reference plane at the center of the ceramic. Then a curve as in Fig. 2 is used to determine displacement of the posts from x=0 to match the *amplitude* of $s11$ for the ceramic. Given the phase of $s11$ for this post displacement, the posts are then translated toward the RF generator from the center of the ceramic to a plane where the *phase* of the ceramic's transformed $s11$ is the negative of the post's $s11$ phase. With this positioning, the impedances of the ceramic and tuning-post obstacles are complex conjugate at the post's reference plane and the assembly is RF matched. The physical distance translated toward the generator is simply the fraction of a guide half-wavelength represented by the phase difference in $s11$ of the individual obstacles,

$$L = \frac{\Delta\phi}{360} \cdot \frac{\lambda_g}{2} \quad . \qquad (1)$$

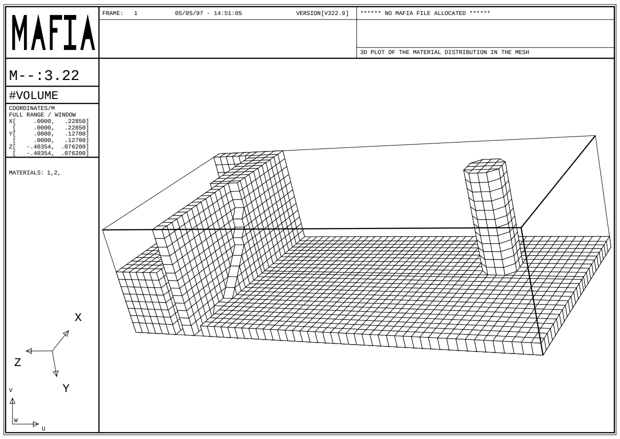

Figure 1. MAFIA-generated plot of a quarter section of a tuning-post matched window, utilizing symmetries to reduce computation volume. The reduction in waveguide height and width after the ceramic is peculiar to a Cornell application.

In the long run, this matching technique saves much effort over the trial-and-error method of tuning-post placement.

In this design, the tuning posts reside in what will be the air side of the vacuum barrier. This is so that the standing wave set up between the posts and the ceramic will not exist in the vacuum region where multipactor and general arcing are most susceptible.

2.2 *Self Matching*

The geometry of a quarter section of a self-matched window is shown in Fig. 3. Matching such a window is a straightforward trial-and-error process where the width of the iris (and consequently ceramic) is adjusted until RF reflection is minimized. In performing this adjustment, the enhanced capacitance of the obstacle due to the dielectric is balanced by the enhanced inductance due to the iris, providing a wave impedance $\sqrt{L/C}$ equal to that of the surrounding waveguide. Fine tuning can also be performed by adjusting the ceramic thickness and iris thickness.

2.3 *Design Subtleties*

It is worth mentioning a couple of design features adhered to in consideration of sound practice for both window types discussed above.

First, at the ceramic-metal-vacuum boundary (so-called triple point), no corners, not even rounded, were allowed on the metal, only on the ceramic. A metallic corner abutting a dielectric is the focus of electric field enhancement exceeding that of a metal corner alone.

Second, the shape of the perimeter of the ceramic plate was kept circular or elliptical, no “flats”. This is to facilitate brazing of the ceramic into a metal sleeve, allowing the sleeve to maintain close contact with the ceramic during brazing, similar to the fit of hoops on a wine barrel. The perimeter of the ceramic and sleeve could also be tapered longitudinally to mimic a press fit.

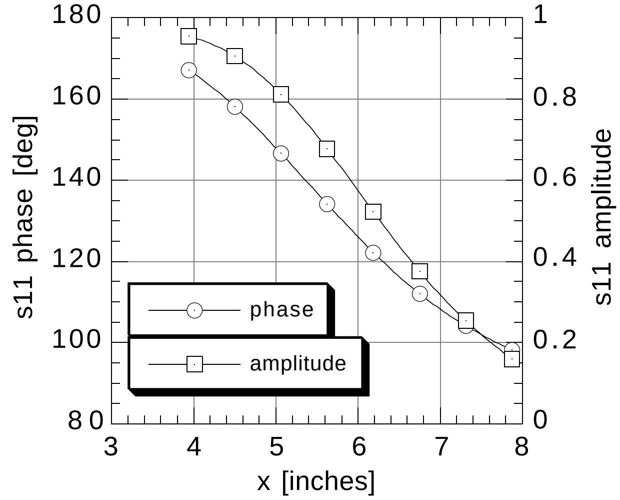

Figure 2. Computed phase and amplitude of $s11$ at 500 MHz for a pair of 1.5" diameter posts symmetrically located about the x=0 plane in WR1800 waveguide.

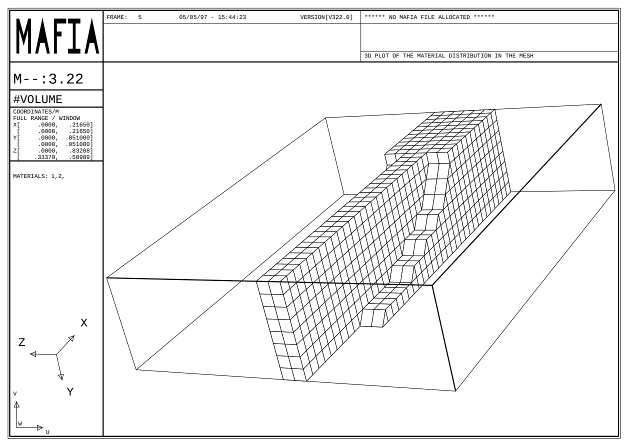

Figure 3. MAFIA-generated plot of a quarter section of a self-matched window.

3 THERMO-MECHANICAL ANALYSIS

Once the RF design is settled, a perturbation calculation can be performed in MAFIA to give the power density dissipated in each mesh cell of the ceramic due to a non-zero loss tangent. This data table can then be manipulated and read into the 3D thermo-mechanical computer code ANSYS. ANSYS is then used to compute the thermal profile of the ceramic and the resultant stresses, where in this study the perimeter of the ceramic is held at a fixed temperature and a 15 psi pressure differential exists across the ceramic.

The location and magnitude of peak stress within the ceramic is closely coupled to how the component is mechanically constrained. For this study, the perimeter of the ceramic was taken to be attached at the center of a 1/8" thick copper sleeve about twice as long as the ceramic. The very ends of the copper sleeve were then taken to be immobile. This is close to what is intended in the final mechanical design

Table 1. Results of ANSYS thermo-mechanical analysis for 1 MWCW propagating at 500 MHz and $\delta = 3\times10^{-4}$.

Ceramic	Waveguide Configuration	Ceramic Perimeter	Ceramic Thickness	ΔT [°C] Center to Perimeter	Max Principal Stress % of Tensile Strength
Beryllia	self-matched red hgt	elliptical	uniform	4.2	2.8
Beryllia	posts, full hgt - red hgt	circular	uniform	5.3	6.8
Beryllia	self-matched red hgt	elliptical	tapered	2.8	8.6
Beryllia	posts, full hgt - red hgt	circular	tapered	4.8	12.7
Beryllia	self-matched full hgt	elliptical	uniform	5.8	14.1
Alumina	self-matched red hgt	elliptical	tapered	51.4	14.7
Alumina	posts, full hgt - red hgt	circular	tapered	105.0	32.1
Alumina	posts, full hgt - red hgt	circular	uniform	130.0	58.1
Alumina	self-matched red hgt	elliptical	uniform	111.0	60.8

where the copper sleeve is part of a cooling water circuit.

It is a matter of interesting discussion as to which type of stress in which ceramic fracture scenario is most important to consider. But to have a common parameter by which different window designs can be compared, the maximum principal stress was chosen as the parameter to be minimized. And as a conservative limit, during window operation this stress should not be allowed to exceed 25% of the ceramic's tensile stress.

An interesting feature explored in this study was to taper the thickness of the ceramic, making it thin at the center and thick at the perimeter. If the cooling circuit is at the ceramic perimeter (fixed temperature), tapering the thickness will result in a lower thermal gradient than uniform thickness. This is since at any radius, the tapered ceramic will have a larger area through which to conduct heat from a smaller bulk-heated volume than if the thickness were uniform.

Table 1 lists the results of ANSYS computations for several window configurations to be discussed next.

4 COMPARISON OF DESIGNS

The results shown in Table 1 are for 1 MWCW propagating at 500 MHz. The effective loss tangent of all ceramics is taken to be 3×10^{-4}. Alumina's actual loss tangent tends to be much smaller, but experience with four Thomson windows at Cornell indicates that the contribution of the anti-multipactor coating can be random and significant, and in the end a coating resulting in $\delta \sim 3\times10^{-4}$ is just about right. It is hoped that industry can fabricate large plates of Beryllia that do not exceed this loss tangent.

From Table 1 it is seen that tapering the ceramic thickness does indeed result in a lower operating temperature. However, for Beryllia, the lower temperature did not translate into lower peak stress since the tapered thickness also altered mechanical loading. For Alumina, the reduction in stress from tapering the ceramic is large enough in only one case to justify the added complexity and cost of ceramic fabrication: the self-matched ellipse in reduced-height waveguide. (The case of a self-matched Alumina ellipse in full-height waveguide had such high temperature and stress, it was dropped early in the study).

The design in Table 1 that shows the greatest promise is the first listed, a self-matched Beryllia ellipse of uniform thickness in reduced-height waveguide. This is the window shown in Fig. 3. This design's peak stress being only 2.8% of Beryllia's tensile strength leaves great margin for error in many fabrication parameters. The only concern is the enhanced electric field in reduced-height waveguide making this design more susceptible to multipactoring. Many MAFIA runs were performed for this window design to map dimensional and material property sensitivity, the result of which showed no drastic dependence within expected tolerances. It is hoped that a prototype of this design will be built and tested.

As fallback positions, the cases of a tuning-post matched Beryllia disk of uniform thickness and a self-matched Beryllia ellipse of uniform thickness in full-height waveguide are quite promising. And finally, the first Alumina case listed in Table 1, a self-matched ellipse of tapered thickness in reduced-height waveguide, may still be considered if Beryllia doesn't prove out in loss tangent or ease of brazing. This is similar to the window shown in Fig. 3.

REFERENCES

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