TESTS AND DESIGNS OF HIGH-POWER WAVEGUIDE VACUUM WINDOWS AT CORNELL

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Abstract

The superconducting cavities for the CESR III upgrade at Cornell utilize rectangular waveguide iris coupling. Waveguide vacuum windows manufactured by Thomson Tubes have been tested off-line at 500 MHz up to 500 kWCW traveling wave, 130 kWCW full reflection, and on-line attached to an SRF cavity with beam. On and off-line window processing characteristics are presented. This experience has yielded insight regarding window processing in traveling wave and full reflection modes coupled with effects of atmospheric exposure. Designs of future windows targeted for 1 MWCW operation are also presented.

1. INTRODUCTION

Operation of superconducting RF cavities in high current storage rings requires RF vacuum windows in the 350-700 MHz range capable of CW operation at power levels of several hundred kW. Common difficulties encountered with such windows are: 1) multipactor discharge and 2) heating of the ceramic vacuum barrier. The first difficulty, multipactor discharge, is a precarious phenomenon usually addressed by applying a sufficiently thick anti-multipactor coating, such as Titanium, to trouble spots. So-called “multipactor barriers” are often encountered during RF processing, whereby the resonant multipactor conditions are satisfied at particular field levels. If a barrier is mild enough, the instigating emitter can be processed away and higher RF power attained. The second difficulty, ceramic heating, is due to both surface heating by the RF-lossy anti-multipactor coating and bulk heating due to the ceramic dielectric loss tangent. Typically, the perimeter of the ceramic is held at a fixed temperature by a cooling water interface and the thermal gradient of the disk interior induces mechanical stress. This will fracture the ceramic at sufficiently high induced stress. Such thermo-mechanical effects will ultimately limit the average power that can be propagated by an RF window.

Presented here will be results of processing experience with four waveguide windows manufactured by Thomson Tubes for 500 MHz operation up to 500 kWCW traveling wave. These windows are used in the superconducting RF upgrade to the Cornell storage ring CESR III [1]. They have been processed off-line connected as pairs with vacuum in between, and one of the windows has been attached to the CESR SRF cavity and operated on-line with beam. These experiments have yielded insight regarding atmospheric exposure of a processed window coupled with operation when attached to an SRF cavity. Off-line window processing has shown the familiar phenomenon whereby less-intensive reprocessing must be performed after atmospheric exposure. On-line window operation, however, has additionally demonstrated a marked difference between traveling wave and full reflection processing. It was observed that reprocessing a window after atmospheric exposure to install it on a cavity proceeded fine without beam (full reflection), but as beam current increased, reprocessing of the window occurred (vacuum bursts) due to the increasing traveling wave component. Such reprocessing with beam is difficult since the beam is often lost due to a vacuum trip. Experience and suggested techniques to reprocess a window in traveling wave mode after attachment to a cavity without beam will be presented.

Finally, designs will be presented for vacuum windows that have thermo-mechanical related RF power limits in excess of 1 MWCW.

2. OFF-LINE PROCESSING

A schematic of a Thomson waveguide window is shown in Fig. 1. It is a “warm” window, maintained at room temperature during operation as opposed to “cold” SRF windows that have components at or near liquid helium temperatures. It operates at 500 MHz with a standard WR1800 flange at one end and reduced height at the other. The vacuum barrier is a 25 cm diameter, 1.7 cm thick alumina disk with matching posts on both the air side and vacuum side. The setup for off-line processing utilizes two windows connected back-to-back with a short pumping and diagnostic waveguide section in between [2]. Window pairs are initially processed with the window furthest from the generator connected to a matched load up to powers near 450 kWCW. The windows are further processed with the load replaced by a shorting plane to place a maximum electric field at either of the window ceramics, up to powers near 130 kWCW. During processing, the ceramic temperature profile is monitored by viewing from the air side with an infra-red camera, a sample image of which is shown in Fig. 2.

Shown in Fig. 3 is RF power propagated vs. time during processing of four windows. The processing rate is limited by requiring the vacuum to be maintained less than 10^{-7} T. In addition to initial processing, also plotted is the case for window pair 3&4 being let up to atmospheric pressure of clean nitrogen gas, pumped out, and reprocessed. For window pair 1&2 in Fig. 3, power levels plotted above 300 kW are peak power with a 33% duty cycle, lowered from CW due to overheating of window #2’s ceramic.

Listed in Table 1 are operating temperatures at the center of the ceramic of the four windows at 300 kWCW and their titanium anti-multipactor coating history. Variation between windows in ceramic operating temperature was due to inconsistent thicknesses of titanium. A temperature difference of 65° C between the ceramic center and edge results in thermally induced stress being 25% of alumina’s tensile strength. This was the initial limit of safe operation imposed on these windows, subsequently raised to 85° C and 33% of tensile strength.

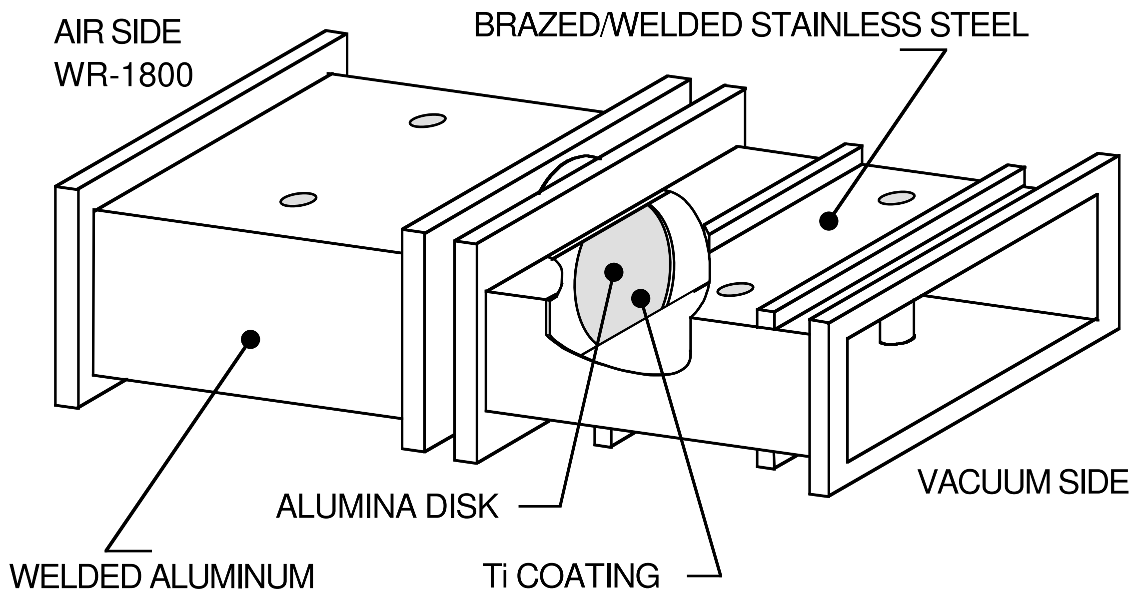

Figure 1. Schematic of a Thomson waveguide window.

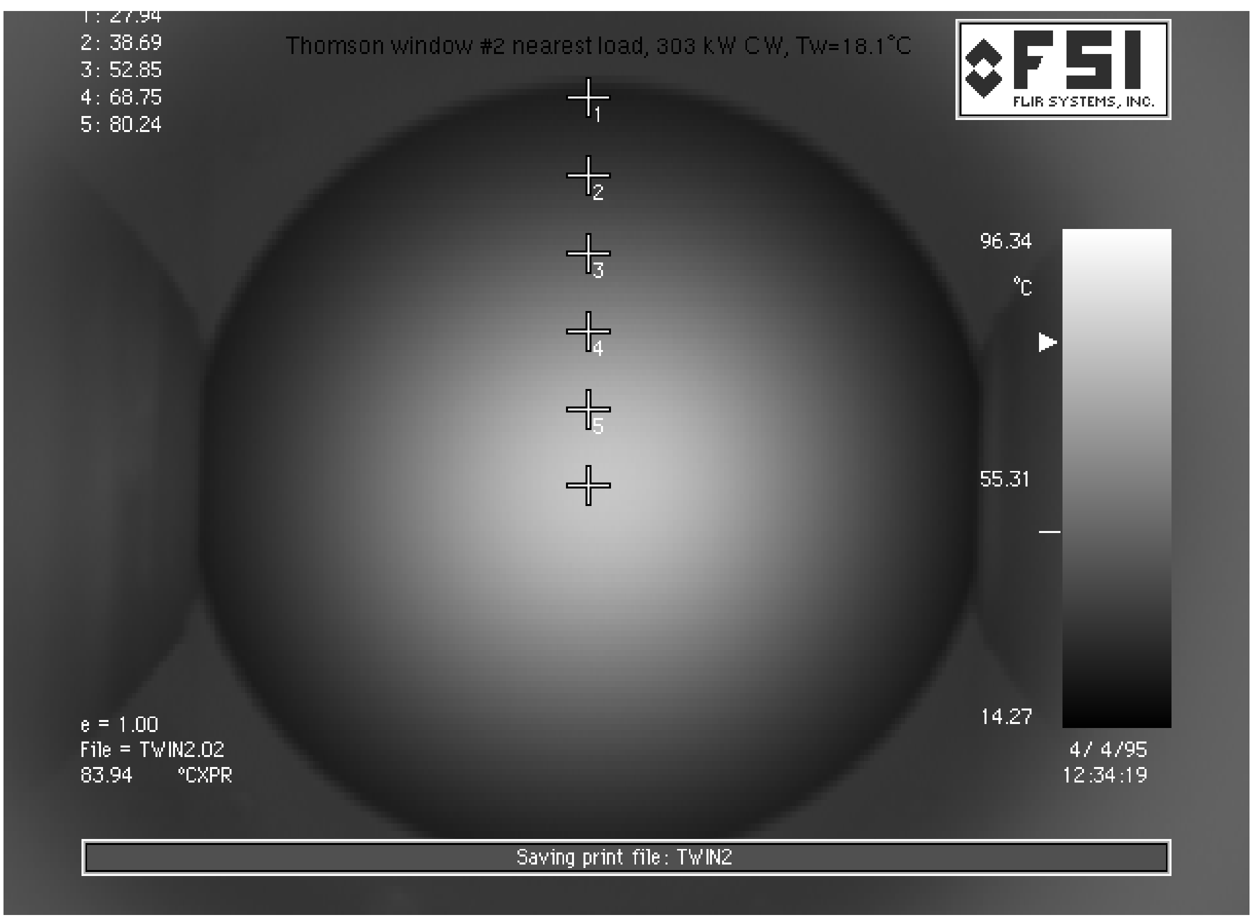

Figure 2. Infra-re image of window #2's ceramic near its maximum CW power level.

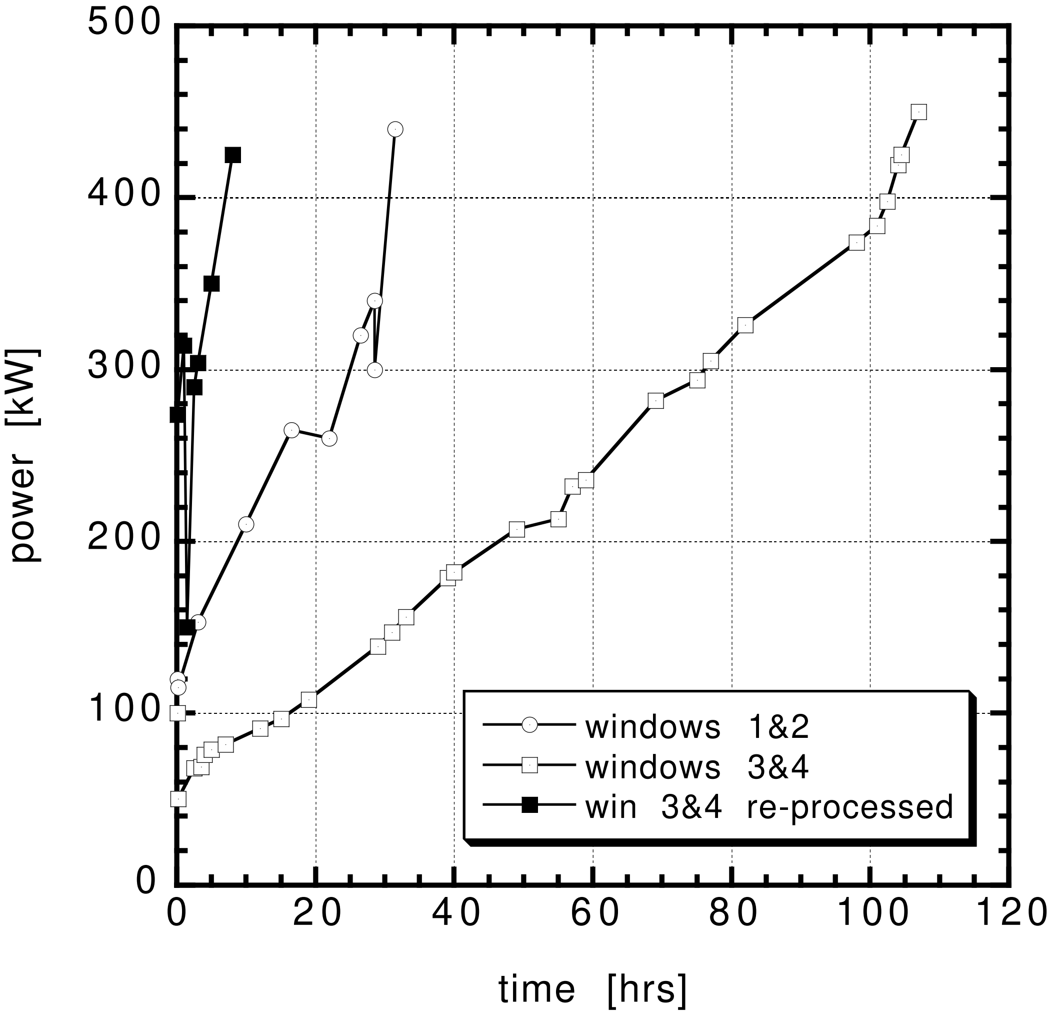

Figure 3. RF power propagated vs. time for processing of two window pairs. In addition to initial processing, also plotted is the case for window pair 3&4 being let up to atmospheric pressure of clean nitrogen gas, pumped out, and reprocessed. For window pair 1&2, power levels plotted above 300 kW are peak power with a 33% duty cycle.

Table 1. Measured ceramic operating temperatures at 300 kWCW and Ti coating history.

Window	ΔT center-to-edge	Titanium Coating
1	44 °C	3-5 nm
2	67 °C	3-5 nm, original coating sandblasted off and re-applied
3	12 °C	2-3 nm, original coating sandblasted off and re-applied
4	22 °C	2-3 nm, original coating sandblasted off and re-applied

The target thickness for the Ti coating on windows 1&2 was 3-5 nm. Window #2, which reached the initial temperature limit at 300 kWCW, had its original Ti coating sandblasted off due to an imperfection and a new coating re-applied. It is suspected that some of the original Ti coating on window #2 may have remained after sandblasting. Windows 3&4 also had their original Ti coatings sandblasted off, but much more vigorously after knowledge of window #2's overheating. Further, windows 3&4 had their final Ti deposition thickness 2-3 nm.

It is interesting to note that window pair 3&4 with the thinner Ti coatings and the lower operating temperatures took much longer to process than pair 1&2, as seen in Fig. 3. It is not clear at this time whether the thinner Ti coating will result in troublesome operation when the window is attached to an accelerator cavity.

After letting up to atmospheric pressure of clean nitrogen gas and pumping out, window pair 3&4 immediately allowed propagation of traveling wave power up to 275 kWCW. At that point there was a vacuum trip requiring reprocessing over several hours to re-establish previously processed power levels near 450 kWCW. The total reprocessing time after atmospheric exposure was about an order of magnitude less than the original processing time. Off-line tests with such atmospheric exposure were not performed in full-reflection mode, the implications of which will be discussed in the next section.

3. ON-LINE PROCESSING

After off-line processing, Thomson window #1 was let up to atmospheric pressure of clean nitrogen gas, attached to the CESR III SRF cavity, and the entire cavity/waveguide region pumped out. The window resides at room temperature beneath the cryostat, as illustrated in Fig. 4. The location of the maximum electric field of the standing wave reflected from the cavity without beam is about 4 cm to the vacuum side of the window ceramic. The window was not vacuum baked after attachment to the SRF cavity.

When the window is attached to an SRF cavity without beam, the window is presented with an effectively shorted load (full reflection) due to the highly over-coupled (β=5000) SRF cavity. As beam current increases, there is an increasing traveling wave component. After cool-down of the SRF cavity in a processing area, the cavity and window were simultaneously processed without beam in its full-reflection state. This processing rate was paced by the SRF cavity's radiation and quench trips. The maximum CW power achieved without beam on cavity resonance was 64 kWCW, corresponding to a cavity field of 8.5 MV/m and voltage of 2.6 MV, obtained after about 24 hours of processing.

The CESR III SRF cavity was then installed into the CESR storage ring, reprocessed without beam for about 2 hours, then injected with beam. Typically, the SRF cavity is operated in CESR at a field of 6.3 MV/m or voltage of 1.9 MV. As the beam current was increased in CESR after the month-long down, hard vacuum trips occurred in the SRF cavity window region at currents

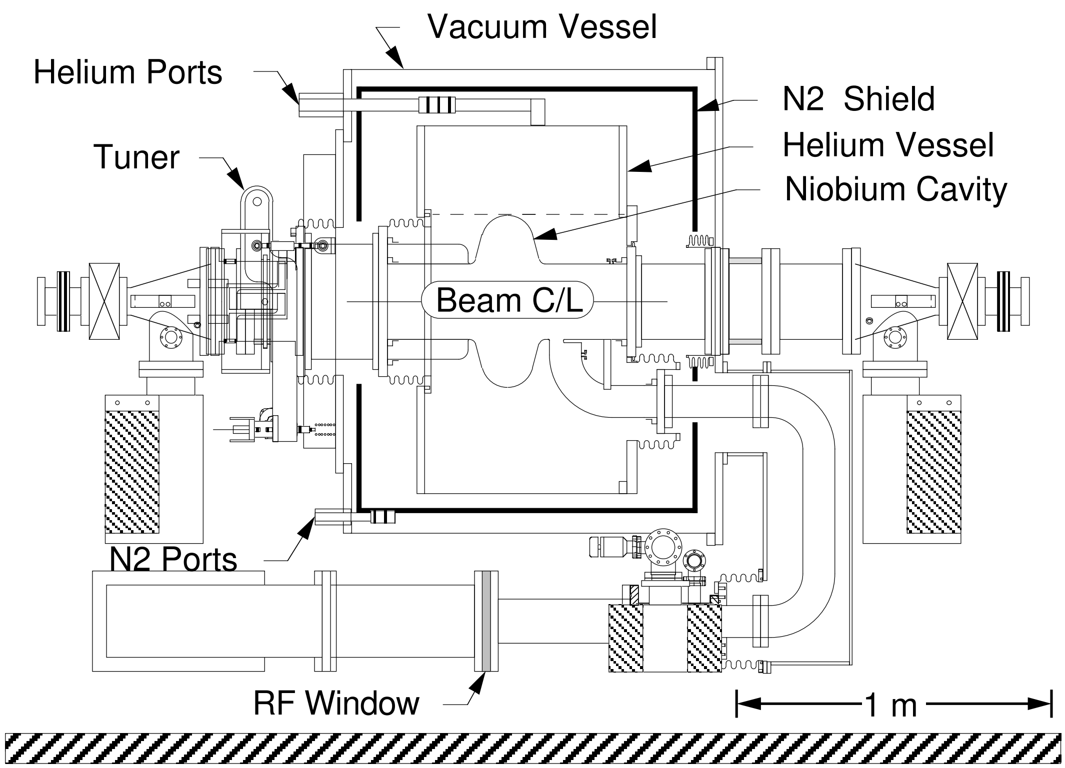

Figure 4. Layout of the CESR III SRF cavity, cryostat, and auxiliary components.

around 230 mA. Scrutiny of all parameters revealed that the vacuum trips occurred when the forward power minus reflected power from the SRF cavity, or traveling wave power delivered to the beam, was 90 kWCW. This was a repeatable limit at several cavity voltages and beam currents. Aggressive window processing without beam and off cavity resonance, up to powers of 160 kWCW, had little effect on the traveling wave vacuum trip limit.

To date several in-situ window processing techniques have been explored, including "beam processing" whereby the beam current is raised close to its limit and injection is stopped as soon as window vacuum activity is detected. Additionally, when vacuum activity is detected, the RF phase between the SRF and other cavities can be adjusted to decrease power to the SRF cavity. This and other techniques, such as configuring external magnets near the window, advanced the traveling wave limit to 110 kWCW and beam current to 320 mA. The beam is frequently lost during beam processing, however, making it slow and tedious.

The greatest success with in-situ window processing to date has been obtained by relaxing the quench limit on the SRF cavity during *pulsed* RF processing without beam. In this technique, the cavity is pulsed with high RF power on resonance to the point it is in the process of quenching, typically 170 kW for 10 ms, at which time the RF coupling gets closer to matched and there develops a significant traveling wave component through the window. Further, for pulses for which the cavity does not quench, when the RF is terminated the cavity dumps its stored energy to the waveguide, producing a large spike of traveling wave power in the opposite direction, typically 300 kW for 10 μs. This technique significantly advanced the traveling wave power limit to 140 kW after a few hours of processing. The CESR beam current is presently limited to 350 mA, where a longitudinal beam instability linked to the normal-conducting RF cavities in CESR disrupts the beam. As the normal-conducting cavities continue to be replaced by SRF cavities in the CESR III upgrade, this longitudinal instability should be relaxed.

Several new window processing techniques will be explored with the second of four CESR III SRF cavities as well as the first SRF cavity already installed in CESR. The main goal of such processing will be to enable a significant RF *traveling wave* component to be propagated through the window after atmospheric exposure and installation onto the SRF cavity. One way to accomplish this is to cool the cavity to about 20 °K where the cold, but still normal conducting, niobium will provide a fair match to the waveguide coupler. Pulsed processing can then proceed without beam into a fairly matched load, taking care to maintain the average power dissipated in the cavity to tens of watts, which is typical of the operational cryogenic load. During off-line processing of windows, rather than using a fixed short in only one position to place the maximum electric field of the standing wave at the ceramic, a constantly moving sliding short will be used to exercise the standing wave over all parts of the windows [3].

It is not certain at this time that the window region vacuum trips originate at the window ceramic. There are other waveguide intrusions in the area that could be the source of stray emissions that instigate a vacuum trip, such as pumping ports, diagnostic ports, and the waveguide thermal transition from room temperature to liquid helium temperature, which is an area rich with condensed gases. In addition to exotic processing techniques, the entire waveguide vacuum region near the window will be modified to increase pumping, eliminate possible stray emitters, enhance diagnostics, perhaps relocate the window ceramic to a standing wave minimum, and perform a vacuum bake prior to cavity cool-down.

4. NEW WINDOW DESIGN

As part of ongoing RF window research and development at Cornell, extensive design studies have been performed to increase RF window reliability and propagation powers to the 1 MWCW regime. In addition to experience such as presented above, designs have utilized the electromagnetic computer code MAFIA linked with the thermo-mechanical code ANSYS to predict thermo-mechanical operational limits for windows. Confidence in such computations is supported by comparisons to measurements performed on several windows. Details of recent designs are presented in reference [4].

Of the several designs outlined in reference [4], the most promising from a thermo-mechanical point of view is a self-matched window utilizing an elliptical beryllia ceramic of uniform thickness in reduced-height waveguide, as illustrated in Fig. 5. This window operates at

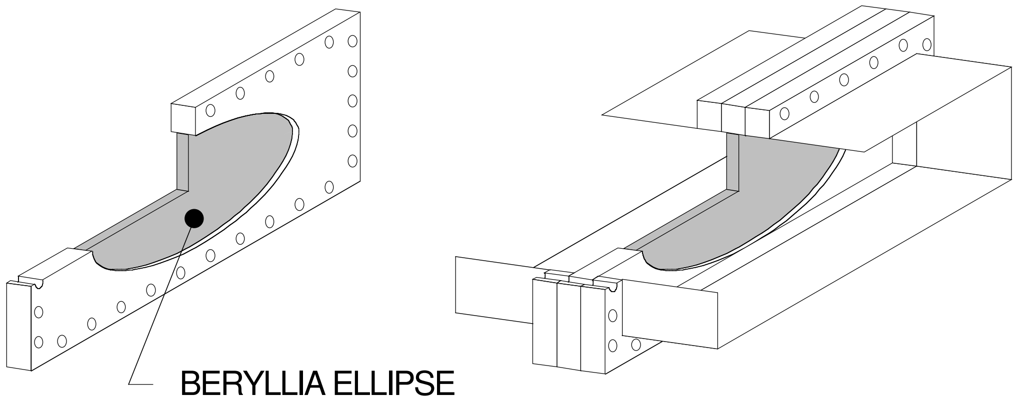

Figure 5. Illustration of a self-matched window utilizing an elliptical beryllia ceramic of uniform thickness in reduced-height waveguide. On the left is the window assembly alone and on the right is the window connected to waveguide.

500 MHz and its advantage is the use of beryllia in reduced-height waveguide. Beryllia has a high thermal conductivity, resulting in lower thermal gradients which more than offset beryllia's lower tensile strength relative to alumina. Also, the reduced-height waveguide shortens the physical length to the water-cooled ceramic perimeter, further lowering thermal gradients and induced stresses.

Several prototype beryllia ellipses for this design have been procured. The mechanical housing must be designed, the window assembly fabricated, and tested at high power. Loss tangents measured on small beryllia samples from the manufacturer [5] have yielded $\delta \sim 1.5 \times 10^{-4}$. It is hoped that the larger ellipses do not exceed this loss tangent. The greatest concern with this window design is the enhanced electric field in reduced-height waveguide possibly making it more susceptible to multipactoring. High power tests will ultimately resolve this issue.

Finally, it is worth mentioning a design feature adhered to in consideration of sound RF window geometry. 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. This is conceptually illustrated in Fig. 6 showing cross sections that could be used in a fictitious ceramic window. The boundary conditions of normal electric field to the conductor, continuity of tangential electric field to the ceramic, and continuity of normal displacement field (εE) to the ceramic contrive to enhance the rectangular waveguide TE_{10} electric field in the vacuum "triple point" region by a factor of ε_r or more. This is borne out by MAFIA simulations and experimental observations of severe arcing at such boundaries. Having the ceramic embedded in a pocket ("Worst Boundary" in Fig. 6) or laying against a step on one side is tempting since it makes brazing

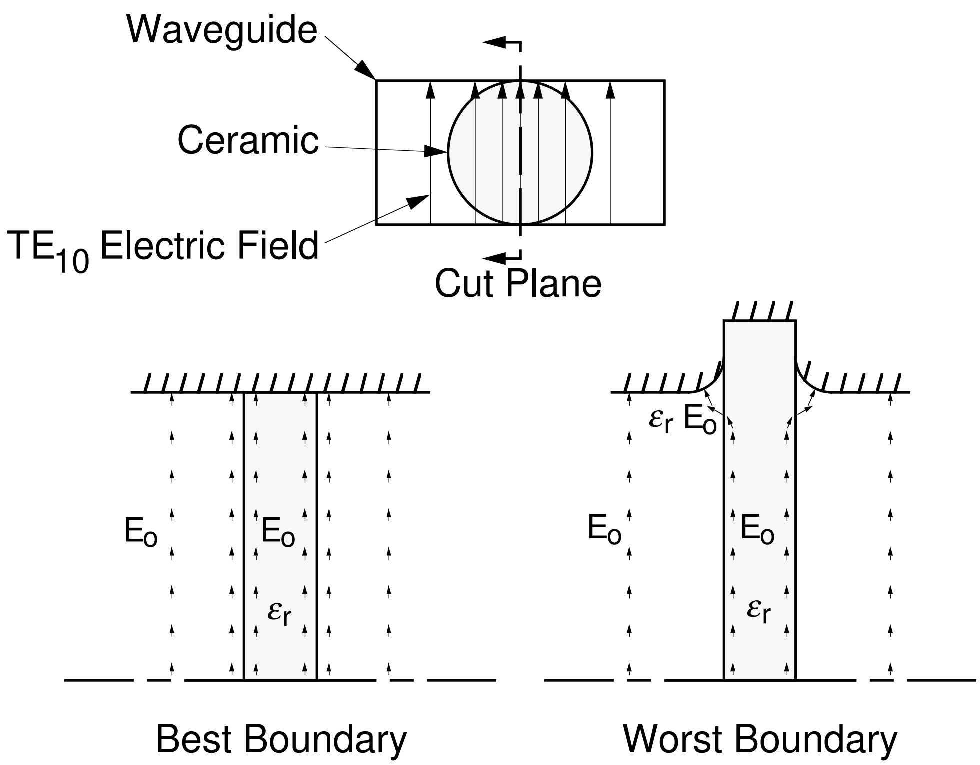

Figure 6. Conceptual illustration of a fictitious ceramic window with cross sections showing the ceramic-metal-vacuum boundary, so-called triple point. Electric field vectors are indicated in the bottom part of the figure with lengths illustratively proportional to field amplitude.

or other seals of the ceramic to the housing much simpler. And many lower power window designs exist with such boundaries and perform satisfactorily. However, great care should be taken before using such a boundary in high average or peak power windows.

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