RUGGED CERAMIC WINDOW FOR RF APPLICATIONS – Phase 1

Final Report for Project end date March 29, 2009.

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RUGGED CERAMIC WINDOW FOR RF APPLICATIONS

Abstract

High-current RF cavities that are needed for many accelerator applications are often limited by the power transmission capability of the pressure barriers (windows) that separate the cavity from the power source. Most efforts to improve RF window design have focused on alumina ceramic, the most popular historical choice, and have not taken advantage of new materials. Alternative window materials have been investigated using a novel Merit Factor comparison and likely candidates have been tested for the material properties which will enable construction in the self-matched window configuration. Window assemblies have also been modeled and fabricated using compressed window techniques which have proven to increase the power handling capability of waveguide windows. Candidate materials have been chosen to be used in fabricating a window for high power testing at Thomas Jefferson National Accelerator Facility.

Background

Recent work at Thomas Jefferson National Laboratory (JLab) has shown that a single, rugged waveguide window may work very well for high-power CW RF coupler applications [i,ii]. JLab is currently in the process of developing a 1.5 GHz waveguide window as part of the development of a high-current cryo-module for Energy Recovery Linac (ERL) and Free Electron Laser (FEL) applications [iii]. The average-power handling requirements for these windows are significantly greater than those anticipated for the International Linear Collider (ILC). Currently, the complicated ILC couplers (TTF-III) can handle peak powers on the order of a megawatt, but the average power handling capability is limited to tens of kilowatts [iv,v,vi].

Although alumina has been the ceramic of choice for decades for RF windows, as RF frequencies increase and the window sizes decrease, the mechanical, thermal, and electrical properties of the window ceramic materials play a more crucial role in determining the ultimate power rating of a window design. Incorporating newer, more advanced ceramic materials into the RF window design will provide increased strength and thermal handling properties to make the window a strong point in the system instead of a weak point.

Technical Approach

The fundamental features of the window design concept championed here include the self-matching nature of the iris depth and ceramic thickness [vii], and a ceramic window that is entirely contained within the aperture of the rectangular waveguide. A key feature that allows the increased power handling capability of this window design is the pre-stressing of the ceramic window to place it into a compressed state so that the tensile stresses that result from RF heating are almost completely eliminated.

The development of the high average-power waveguide windows at JLab [xi,xii,xiii] has been based on this design concept, which has led to very reliable and cost-effective solutions. The concept has been used successfully for the SLAC B-factory and Spear-3 light source at lower frequencies [viii]. Figure 1 shows a similar 700 MHz design, which was developed for LEDA at LANL [ix] and was tested to almost 1 MW CW.

Pre-stressing is accomplished during the brazing process, where the differential expansion properties of the materials are used to precisely control the gaps to provide a quality braze, resulting in a compressed ceramic after cooling.

Figure 1: Left: Schematic layout of the 700 MHz waveguide and window assembly. Right: The assembled 700 MHz MW-class waveguide window.

Figure 2 shows a schematic section of the braze fixture used in producing the 700 MHz window [xiv]. The window piece itself consists of a ceramic disk that is metalized and brazed to a stainless steel ring that is copper plated on its inner surface. The copper plating provides a contiguous copper buffer layer. Initially, the ceramic is slightly smaller in diameter than the stainless steel flange piece, and the stainless steel is confined by a molybdenum ring. Molybdenum and alumina (used in the 700 MHz

window) have approximately the same thermal expansion coefficient, with that of alumina slightly larger, while stainless steel has an expansion coefficient that is more than a factor of 2 larger than either molybdenum or alumina. As the oven temperature increases, the stainless steel tries to expand more than the molybdenum ring will allow. Stress builds up in the stainless steel until it reaches the yield point and relieves that stress by plastic deformation. As the oven temperature rises, the expansion of the alumina is slightly larger than that of the molybdenum and hence, slightly larger than that of the confined stainless steel. The key engineering step is to determine the precise starting dimensions of the material so that when the braze temperature is reached, the gap between the freely expanding ceramic and the molybdenum-confined stainless steel is precisely that required for a quality braze (0.001" – 0.003"). As the part cools, the stainless steel flange will try to contract more than the ceramic window or molybdenum ring. Because of the plastic deformation of the stainless steel, it will separate from the molybdenum ring as it cools, but will radially compress the ceramic.

The copper buffer layer is a critical component of the cool-down cycle. The thickness of the copper and its soft mechanical properties at around 400C allows for stress relieving of axial stresses as the braze cycle is designed to do when using a hold period of about 10 hours at 400C.

With a carefully controlled cooling profile so as to prevent any thermal gradients, the stainless steel ring will provide uniform compression of the ceramic disk. Once the part is removed from the furnace and leak tested, the stainless steel outer ring is then ready for subsequent machining and assembly into the window hardware.

Figure 2: Material layout for the brazing of the 700 MHz RF window showing the alumina ceramic window, the water-cooled copper-plated stainless steel flange, and the outer molybdenum ring used to confine the stainless steel during brazing.

JLab has begun a program of developing these windows at 1497 MHz as used at its primary CEBAF machine, its 12-GeV upgrade, and its FEL. Figure 3 shows the ceramic window in the brazing fixture prior to being placed in the oven (*left*) and the window after being brazed and leak tested (*right*).

Figure 3: Left: 1.5 GHz ceramic window in fixture prior to brazing. Right: Brazed ceramic window ready for machining. The critical gaps before brazing are shown: a) molybdenum keeper ring to stainless steel compression ring, and b) the ceramic window to stainless steel compression ring.

In this project, we investigated and tested different ceramic materials for use in the high average-power RF windows and ultimately constructed and tested windows with better performance than those based on alumina. The nature of the manufacturing and operating conditions of these windows required that the window material be sufficiently strong mechanically, minimally absorbing of RF power (low loss tangent), and have a thermal conductivity as large as possible. As with the design of any piece of equipment, a balance between parameters had to be made.

Public Benefit

As the development of the next generation of superconducting RF cavities for use in ERLs and FELs progresses, the power handling requirements of the RF components also increase. The development of more robust windows will benefit any RF user who wishes to increase the average power delivered to an individual cavity. The development, standardization, and commercialization of rugged windows will benefit any user wishing to get maximum performance at minimum cost.

Windows of this type would be of direct benefit to the Thomas Jefferson National Accelerator Facility in their ongoing efforts to design and build ERLs and FELs. In particular, the JLab IR Upgrade FEL was operationally limited by an RF window that can handle only 40 kW [x].

Some of the materials that were investigated in this project are optically transparent in the visible range, which allows a new way to monitor the window performance for feedback during setup and real-time alarm reporting during operation. Optical techniques such as interferometry will be able to identify the *impending* failure of a window to prevent damage and lost time that would result from a failure of vacuum integrity in a cryogenic cavity.

Degree to which Phase I has Demonstrated Technical Feasibility

The specific technical objectives of the Phase I project included:

- 1) Determination of the materials to be tested.
- 2) Performing electromagnetic design of the 1497 MHz RF waveguide window using identified materials.
- 3) Performing thermal and mechanical finite element analysis of the waveguide window(s) to assure structural integrity during full power operation.
- 4) Obtaining samples of the ceramics deemed to meet the mechanical and RF requirements based on the simulation studies, and testing of those samples at the desired RF frequency.
- 5) Designing a device to monitor properties of optically transparent windows under power.

1. Determining the materials to be tested

In order to make choices among various ceramics for microwave windows based upon thermal considerations, it appears that the ratio of thermal conductivity to loss tangent may be a meaningful merit factor. The reasoning is as follows: for every watt generated by the losses in the ceramic as a function of the loss tangent ($\tan \delta$), the temperature differential required to remove that watt is determined by the thermal conductivity (k) of the material, so a high value of the ratio is good.

Furthermore, if the ratio "*Merit Factor*" = $\frac{k}{\tan \delta}$ remains constant at low temperatures,

then the variation in $\tan \delta$ with temperature will have no impact on the thermal stresses in the window because the temperature profile from the center to the edge will remain constant. This suggests a way to make meaningful judgments about the relative merits of various ceramics.

A survey of the NIST data for thermal conductivity is summarized in Figure 4 below.

Figure 4: Thermal Conductivity of various potential window materials as a function of temperature.

Room Temperature Data (approx 1 GHz)			
Material	Loss tangent $\tan \delta$	Thermal Conductivity W/m/K	Merit Factor $\times 10^6$
Al ₂ O ₃	0.00018	31.5	0.179
BeO	0.00110	251.5	0.229
BN	0.00025	61.0	0.244
SiC	0.00360	129.8	0.036
SiN	0.00360	26.3	0.007
ALN	0.00195	154.0	0.079
Sapphire	0.00001	38.0	3.800
Transtar	0.00010	35.0	0.350
Shapal-M	0.00700	90.0	0.013
ALON	0.00031	9.5	0.031

Figure 5. Merit Factor for various materials.

Figure 5 summarizes the calculation of the *Merit Factor* using published data from various sources. If there were ranges of data from various sources, simple averages were used for $\tan \delta$ and k , and where necessary, the data was scaled in frequency ($\tan \delta \propto f$) so that the *Merit Factor* shown is for 1 GHz at room temperature.

Figure 6. The same data as shown in Figure 5, plotted as a bar chart

The table and chart above indicated that BeO and BN are good choices based on *Merit Factor*. We chose not to include them in the Phase I study because of other material factors. In the case of boron nitride we did not choose it because of its low compressive strength of about 34000 psi. The compressive strength of the material is critical to the construction technique of the compressed window. In the case of alumina, aluminum nitride, sapphire, and transtar, the compressive strength is about an order of magnitude larger than that of boron nitride.

As for BeO, there are published safety concerns for the material based upon the requirements to properly dispose of the dust during the manufacture and material

handling. There have been many improvements in this regard during the last ten years, but we did not want to cloud our results with perceptions of safety issues.

Therefore, the three materials chosen for the Phase I analysis were the remaining three materials, other than alumina, with the largest *Merit Factor*: Aluminum Nitride, Sapphire, and Transtar®, which is a proprietary aluminum oxide with high purity from Cerradyne.

2. Perform electromagnetic design of the 1497 MHz RF waveguide window using identified materials.

Once a design was completed for the self-matching window, the electromagnetic design of the 1497- MHz RF window depended only on the dielectric constant of the window material and a window thickness approximately equal to a quarter wavelength; the lower the dielectric constant, the thicker the window. Figure 7 shows a schematic of the window designed to fit the height of WR650 waveguide. The thickness and dielectric constant of the window determine the match frequency of the assembly.

Figure 7: The electromagnetic design fits the window into the height of WR650 waveguide.

3. Perform thermal and mechanical finite element analysis of the waveguide window to assure structural integrity during full power operation.

The construction and modeling of the compression ring.

The compression ring design has three main requirements:

- 1) The finished window must be left in a pre-stressed condition with radial forces only.
- 2) During cool-down and radial compression, axial forces that can put the window edge under damaging axial tensile stress must be relieved by a copper buffer layer.

- 3) The compression ring must contain a channel for liquid coolant.

Construction of the buffer layer is typically done by plating large amounts of copper on the stainless steel ring. This is time consuming and costly. A better way was investigated in this Phase I program. A copper ring was brazed into the inside diameter of the stainless steel ring. This braze is not trivial and requires significant process controls to minimize braze gaps between the copper and stainless steel which can lead to hot spots in the final assembly. In addition, the copper buffer layer was designed to be .020" thick, and post machining the assembly may have lead to removing too much copper so that the buffer layer would not be effective. Figures 8, 9, and 10 show examples of the braze gap, a thin buffer layer, and a perfect buffer layer, respectively.

The process technique for making the buffer layer is critical to the construction of rugged ceramic windows.

Figure 8: Shows proper thickness of the copper buffer layer, but also a braze gap between the copper and stainless steel that may lead to hot spots during operation.

Figure 9: Good braze joint, but copper thickness is about half what it should be.

Figure 10: Good braze (no gaps) and good thickness of buffer layer.

During the brazing of a completed window, the stainless steel compression ring goes through a critical extrusion process. The extrusion results in a ring that is smaller in diameter at room temperature than it started out, and it is this reduction in diameter that makes the pre-stressed window. Modeling the extrusion process is a critical first step in calculating the amount of pre-stress in the completed window. The ANSYS model of the extrusion process is shown in Figure 9. From 25C to 200C, the outside diameter of the stainless steel compression ring grows at the rate of the thermal expansion of stainless steel as shown by the slope of the curve. At 200C, the stainless steel compression ring has touched the inside diameter of the molybdenum keeper ring, and must now grow at the rate of thermal expansion of the molybdenum as shown by the reduced slope of the curve. Because the outside of the stainless steel is restrained by the molybdenum keeper ring, the inside diameter of the stainless steel compression ring gets smaller. The stresses inside the stainless steel exceed its yield strength at the elevated temperatures, so that at cool down from 1000C to room temperature, the diameter of the compression ring is smaller than it was at the beginning of this process.

Figure 11. ANSYS model of the extrusion process with a starting gap between the compression ring outside diameter and molybdenum keeper ring inside diameter of .006 in. The red curve is the outside diameter of the compression ring, and the blue curve is the inside diameter of the compression ring.

The ANSYS model of this process compares well with the actual results as shown in the photo of Figure 10. It is important to note that in the ANSYS calculations the starting gap between the keeper ring inside diameter and the compression ring outside diameter were variables in the calculation. The large changes in some of the actual rings are therefore due to starting gaps near zero.

ANSYS Calculations		
Starting Gap	Change in diam, in.	
	ID	OD
0.010	-0.032	-0.029
0.006	-0.041	-0.037
0.004	-0.045	-0.041

Actual Ring Changes		
Ring Number	ID	OD
3	-0.051	-0.032
4	-0.032	-0.02
5	-0.019	-0.018
6	-0.019	-0.018
7	-0.049	-0.046
9	-0.02	-0.018
12	-0.025	-0.014

Figure 12. Calculated and actual changes in the inside and outside diameters of the compression ring after the extrusion process. Large changes indicate small starting gaps.

Brazing and Modeling of the Brazing Process

During brazing the critical starting variables are the gaps between the ceramic window and stainless steel compression ring, and the gap between the stainless steel compression ring and the keeper ring. These gaps determine the final stresses in both the compression ring and the window after brazing and cooling down. As shown in Figure 11, the object is to have no stress on the window at the start of brazing, or else the stainless steel compression ring will be further extruded with a larger ID and less pressure will be exerted on the window at room temperature. In addition, if the gap at braze temperature is not correct, the braze material will not flow properly throughout the joint.

Compression on the Window		
The gap between the keeper ring and the compression ring before braze = .006 in	Gap Between Window and Compression Ring Before Brazing	
	.010 in	.006 in
Compression at Braze Temp	0 psi	4844 psi
Final Compression	26780 psi	26608 psi

Figure 13: ANSYS calculations of the final compression on the window as a function of starting gap between the window and the stainless steel compression ring. The gap between the compression ring and the molybdenum keeper ring is fixed at .006 in.

The compression on the window at room temperature is also limited by the yield strength of stainless steel at room temperature. As shown in the following ANSYS calculations, the stainless steel compression ring has reached its maximum yield strength in tensile 289 MPa (41900 psi).

Figure 14: Axisymmetric ANSYS calculations of the braze cycle showing the deformation of the stainless steel compression ring after cool down and the maximum principal stress (tensile). The region of the compression ring that is in compression is at the copper buffer layer (not shown in this detail).

Figure 15: Axisymmetric ANSYS calculations of the braze cycle showing the deformation of the stainless steel compression ring after cool down and the minimum principal stress (compression). The window is uniformly compressed.

The amount of pre-stress in a disk window determines the allowable temperature difference between the center of the window and the outer edge, as shown in Figure 16.

(a)

(b)

(c)

Figure 16: Axisymmetric ANSYS calculations of the alumina window with temperature profile (a), resulting stress (b), and (c) deformation. The temperature profile was generated by uniformly depositing 62 watts in the alumina window, and removing the heat at the perimeter maintaining a 22C outer edge. The tensile stresses in the window (b) are the result of the expanding center being restrained by the outer edge. The deformation of the width of the alumina ceramic window at the center is a total of 6.2 microns as shown in (c).

With pre-stressing, the outer edge is biased so that greater temperature differentials can be safely maintained. Figure 17 below shows that the pre-stressing designed into the brazing process to make it more rugged, allows the window to handle five times the power one would normally call the limit (using 50% of the tensile limit as a reasonable operating condition.)

uniform heating		Temperature		Edge Tensile Stress		% of limit	
w/mm ²	total watts	center	edge	MPa	psi	w/o pre-stress	w/pre-stress
0.05	16	48	22	33	4785	32%	-147%
0.07	22	58.33	22	46.45	6735	45%	-134%
0.1	31	73	22	66	9570	64%	-115%
0.2	62	125.8	22	132.72	19244	128%	-50%
0.25	78	151	22	165	23925	160%	-19%
0.3	93	178	22	199	28855	192%	14%
0.35	109	204	22	232	33640	224%	46%

Figure 17: ANSYS calculations of the edge tensile stress in alumina and the projected increase in power handling capability as a result of pre-stressing.

4. Obtain samples of the ceramics deemed to meet the mechanical and RF requirements based on simulation studies, and test those samples at the desired RF frequency.

Figure 18: Windows samples of sapphire, aluminum nitride, and Transtar®

The samples of ceramic window are shown in Figure 18 along with the test fixture which has the iris dimensions of the design and fits between WR650 waveguide as shown in Figure 19.

Figure 19: Test fixture with iris and window in WR650 waveguide.

Sample	Thickness (in)	Resonant Frequency (MHz)	Δ Freq from 1497 (MHz)	S21 (db)
Sapphire #1	0.298	1512.125	15.125	0.02
Sapphire #2	0.297	1513.250	16.250	0.019
Aluminum Nitride #1	0.331	1489.312	-7.688	0.224
Aluminum Nitride #2	0.331	1493.600	-3.400	0.222
Transtar #1	0.290	1525.061	28.061	0.171
Transtar #2	0.289	1523.438	26.438	0.126

Figure 20: Test data from the cold test fixture.

The thickness of the samples were designed to be a simple scaling of the published dielectric constant compared to the alumina window and its published data. The degree to which the measured frequency differs from 1497 MHz indicates the error in knowing precisely the dielectric constant of the samples. With this data, one can now proceed

along a well defined path to build a window, with the materials chosen to be precisely resonant at 1497 MHz.

It is interesting to note that the difference in resonant frequency of the aluminum nitride samples suggest a variation in dielectric constant among the samples that is about twice that of the other materials. On the other hand, the published data seem to be more accurate for the aluminum nitride, since with its larger predicted thickness, the resonant frequency was the closest to the desired frequency.

While the S21 value at the resonant frequency during the cold test, in the set-up shown in Figure 19, is not exactly a measure of the loss in the window, it is very close when neglecting WR650 wall and iris losses. The ratios of S21 for aluminum nitride and Transtar® with respect to sapphire are not what one would have expected from the published data shown in Figure 5. This is an interesting result and deserves further analysis.

5. Design a device to monitor properties of optically transparent windows under power.

In the Phase I proposal, it was thought that, since some of the candidate windows would be optically transparent, new optical ways to monitor them could be developed. While this is true, we have discovered that techniques that are used by the JLab FEL people to check the uniformity of mirrors may be perfectly adaptable for our purposes, and we started to make arrangements to work with them on this idea.

Also, vacuum windows used to introduce the laser beam for RF photo-injectors must be distortion free, so the technical issues of measuring these types of windows are well understood and well documented [xv] using the WYKO-6000 interferometer that employs a He-Ne ($\lambda=632.8$ nm) laser test beam with 150 mm diameter aperture. Various types of window measurement techniques have been investigated, and we planed to use the transmission measurement with a WYKO type interferometer. The errors described in reference [xvi] “Measurement of the inhomogeneity of a window” are well within the types of deformation we expect to experience during high power testing.

Fig. 21. Measured surface profile of a fused silica window using the WYKO interferometer [xv]

Since window homogeneity is already being measured for optical purposes, we did not consider it to be a big deal to adapt these measuring techniques to our application with the transparent sapphire and ALON windows. Furthermore, the real issues involved would be fitting the equipment into the high power test stand used for window testing, and this is not complicated since it involves designing waveguide plumbing to allow for a transmission test.

Conclusions

As the development of the next generation of superconducting RF cavities for use in ERLs and FELs progresses, the power handling requirements of the RF components also increase. The development of more robust windows will benefit any RF user who wishes to increase the average power delivered to an individual cavity. The development, standardization, and commercialization of rugged windows will benefit any user wishing to get maximum performance at minimum cost.

Windows of this type would be of direct benefit to the Thomas Jefferson National Accelerator Facility in their ongoing efforts to design and build ERLs and FELs.

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