Thin Beryllium Windows - Analysis and Design Status

Muon Cooling Project - Muon Collider and Neutrino Factory Collaboration

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ABSTRACT

The cooling channel for a muon collider or neutrino source may utilize thin beryllium windows situated between cells of RF cavities. The windows for an 800 MHz design are composed of 16 cm diameter circular foils of 127 micron thickness. These windows undergo significant ohmic heating from RF power, and displace out of plane. This displacement causes the cavities to detune, and must be controlled. In order to evaluate different window designs, an FEA model was created in ANSYS, and this model was correlated to windows tested in the laboratory. The models discussed in this paper are an extension of previous work [3], now incorporating pre-stress effects which are induced in the foil during cool down from brazing. Using empirically validated models, several other window designs are analyzed, including windows of different thicknesses, non-constant thickness windows ("stepped" designs), windows with surface ribbing, and windows of diameters much larger than 16 cm (up to 42 cm diameter). These alternative designs are also subjected to expected RF power loads, and their prospects for operating within strict mechanical tolerances are judged.

Introduction

One design of RF cavities (the so-called "pillbox") being considered for the muon cooling channel in either a muon collider or neutrino factory contains windows of 127 micron thick foils of high purity IF1 beryllium. For the muon collider proposal, these windows are situated in cavities which operate at 800 MHz, with a foil radius of 16 cm; for the neutrino factory, on the other hand, windows operating at 200 MHz with diameters of 38 cm or more are being considered. Each foil is brazed between two annular rings of lower purity PS200 beryllium, with annuli of 16 mm and 40 mm for the 800 MHz and 200 MHz windows respectively; the rings are each approximately 1.6 mm thick (Figure 1). These window assemblies are used in a chain of RF cavities, where the RF frequency is highly dependent on the flatness of the window. The deflection tolerance required to keep the RF cavity frequency shift below approximately 10 kHz is 25 microns, or 1 mil. This tight tolerance is derived at from an estimation of the frequency shift that can be tolerated, combined with frequency versus displacement measurements made on a cold test model cavity [1]. Since the windows undergo significant ohmic heating, and this heating causes deflection, it is critical that the deflection under a given power load is predictable and well understood. The goal of this research is to develop a computational model which allows us to determine window deflections under different power loads and thicknesses, to compare this model with experimental results, and to apply the model to possible design solutions.

In order to experimentally determine the window's response to heating, two 800 MHz Beryllium test windows were fabricated and tested by heating with a halogen bulb [1,2]. These tests showed that the windows did not displace linearly with temperature gradient (as would be expected in a linear-elastic system); rather, they showed no displacement up until a particular temperature gradient, and then began to displace. This behavior is easily explained by the presence of pre-stress in the window. This pre-stress is introduced during cool-down from brazing temperature, due to the fact that the foil exhibits a higher CTE than the annular rings. The amount of pre-stress, however, is difficult to determine due to uncertainties in the CTE of the rings, the CTE of the foils, and the temperature at which the bonding actually occurs.

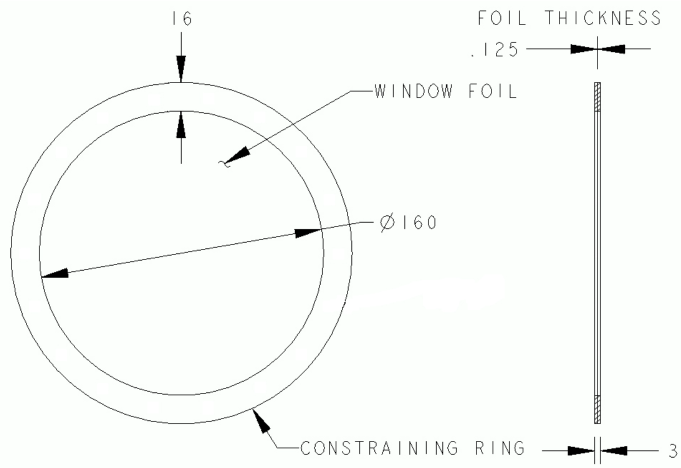

Figure 1. Layout of Beryllium test window (all dimensions in mm).

The goal of all window research was to create a predictive ANSYS finite element model. In order to validate this model, we first obtained empirical displacement results from a window with no pre-stress, which could more easily be compared to FEA calculations. Due to the cost and complexity of working with beryllium, an aluminum window was created with the exact dimensions of the Be test window. Instead of being brazed, however, this aluminum window was bolted together in order to insure that no pre-stress would be included. The FEA model of the aluminum window compared very well with experimental results, usually predicting the observed displacements within 5%, which is well within the known range of material properties [3]. A representative displacement plot of the model is shown in Figure 2.

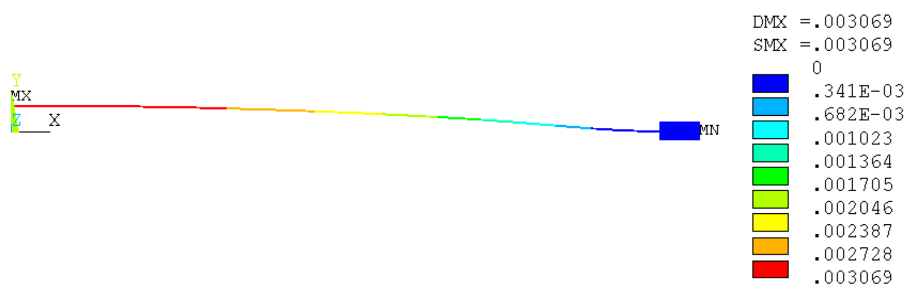

Figure 2. Representative displacement shape of ANSYS FEA model (displacements shown in meters).

The pre-stressed Beryllium windows, however, proved far more difficult to model. Firstly, the pre-stressed model is very sensitive to the coefficient of thermal expansions (CTE) of the materials and how these properties vary with temperature. Secondly, very little data is available on the properties of high purity IF1 versus lower purity PS200 Beryllium. Thirdly, the temperature at which brazing occurs is only approximately known. In order to build a reliable model of the pre-stressed window, the model had to be created, compared to experiment, fiducialized, and then re-checked. This iterative process was used to arrive at a "best fit" model for design purposes.

Comparison of Baseline Models to Empirical Data

The first step in creating a pre-stressed model was to determine the properties and boundary conditions. Since it was found previously that the geometric (radial) constraints on the window were inconsequential, these were omitted from the model [3]. The free variables were:

1) room temperature CTE of high purity foil (IF1)
2) room temperature CTE of lower purity plate (PS200)
3) CTE temperature dependency for IF1
4) CTE temperature dependency for PS200
5) brazing temperature

The brazing temperature was known to be approximately 600 C, and this was held constant; any errors between it and the actual temperature were compensated for by adjusting the CTEs of the beryllium components. Published data for CTE temperature dependency showed a very linear correlation above room temperature so it was assumed that the two materials, which differ in oxide content by less than two percent, would both exhibit linear behavior [4]. It was also assumed that the slopes of the two CTE curves would be equal, offset by some constant value (referred to as the CTE "mismatch" between the two types of beryllium). These assumptions left two free variables to determine - CTE mismatch and base CTE of one of the materials. By running models with different power loads and comparing their maximum displacements to the empirical displacement data, we were able determine the two free boundary conditions necessary to define the model.

In practice, however, this task proved to be far more difficult than originally anticipated. For reasons that remain elusive, the ANSYS model could not be forced to fit the empirical data for all power settings that had been measured. It was decided that too many assumptions about the CTE behavior had been made, and that it was not clear exactly how ANSYS was interpreting that data. In order to simplify the model, the CTE was chosen to be constant with temperature. The CTE of the higher purity foil was chosen, and that of the annular rings was given by a difference from the foil (the "mismatch"). By varying the CTE and mismatch over a significant range, we arrived at a solution that matched the empirical data much more closely, particularly at smaller displacements, where we were most interested. Both linear and constant CTE solutions are shown in Figure 3, together with experimental displacement results.

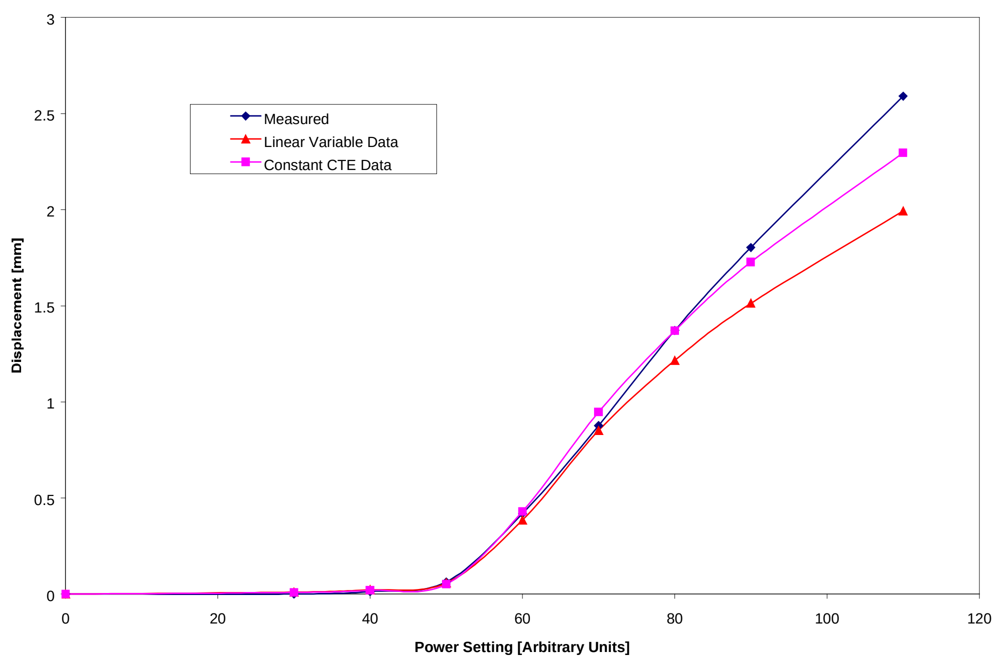

Figure 3. Maximum displacement as a function of power dissipated in halogen heating bulb, for two FEA models and empirical test model.

In these models, the variation of CTE with temperature is given by the function 0.007*T+9.7, with a mismatch of 0.5 ppm/K, where T is the material temperature in Kelvin. For the constant CTE solution, the CTE for IF1 foil (the base CTE), is 11.5 ppm/K, while the mismatch is 0.63 ppm/K. Both of these solutions were arrived at through a long optimization process, and represent the best solutions that could be achieved.

The constant CTE solution fits the empirical data better over the entire range of power settings. However, this range corresponds to the full power range of the heating bulb; in actuality, we are most concerned with the model's performance in the region of small (<0.5 mm) displacements. This region corresponds to the point at which the model transitions from pre-stressed to stressed (or from tensile to compressive stress state in the foil). Table 1 shows the rms deviations between model and empirical data, as well as the maximum differences, for displacements below 0.5 mm. It can be seen that the constant CTE solution exhibits both lower maximum deviations and lower rms deviations. Since only the constant CTE solution shows deviations that are within the 25 micron design tolerance, it was chosen as the baseline model.

Table 1. Deflection comparisons of possible baseline models to empirical results.

CTE Model	Max Deflection Difference From Empirical Data [mm]	RMS Deflection Difference From Empirical Data [mm]
Constant (< 0.5 mm)	0.011	0.009
Linear (< 0.5 mm)	0.034	0.017

Real World Loads vs. Finite Element Loads

The empirical displacement data collected for this analysis was driven by heating from a halogen bulb, which produces a parabolic temperature distribution in the Beryllium foil [1]. RF heating, however, produces a temperature distribution that is flatter than parabolic, as shown in Figure 4. To allow for comparison, the models created in ANSYS were loaded with parabolic temperature distributions corresponding to the measured distributions in majority of experimental cases. The displacement produced in a window is dominated by the temperature rise in the window (difference between maximum and minimum temperatures); the shape of the temperature profile is secondary, but not inconsequential. Thus, while examining the model's response to known parabolic temperature distributions is useful for comparison, it must be analyzed with the expected RF temperature profile in order to judge whether it passes the 25 micron tolerance under real world conditions.

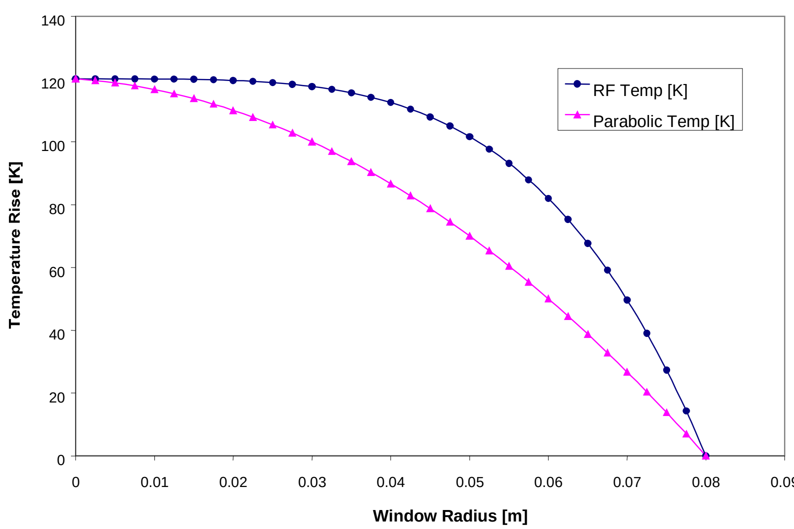

Figure 4. Different temperature profiles with the same overall dT.

The two temperature profiles shown in Figure 4 have been scaled so that they reflect the same maximum temperature rise. Previously it was noted that the model was constructed to fit the empirical parabolic temperature load data as closely as possible. Using the same temperature rise, the model can also be run with the RF temperature profile, in order to quantify the differences between the two temperature loadings. Figure 5 shows the displacement of the baseline model (constant CTE) with both parabolic and RF temperature distributions, compared to the measured data (parabolic temperature load). There is good agreement for the two parabolic results.

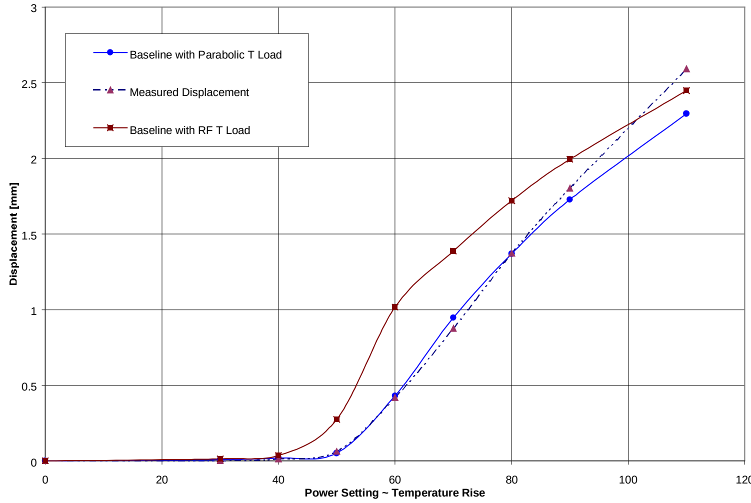

Figure 5. Displacements of baseline model under RF and parabolic temperature loads (with the same overall temperature rise).

As noted earlier, we are primarily interested in the point at which the model's displacement exceeds the 25 micron tolerance. This point indicates the "safe" temperature rise (for a given temperature loading shape) that the window can withstand while remaining within mechanical tolerances. Figure 6 shows a view from Figure 5 over the 100 micron displacement region, along with indications of the expected temperature rise for a 25 micron displacement at the center of the foil.

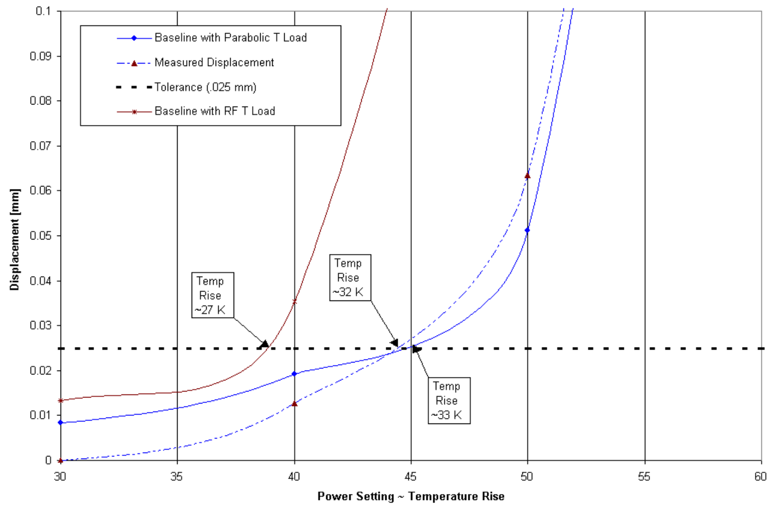

Figure 6. Close-up of 25 micron tolerance regime for baseline model under RF and Parabolic temperature load shapes.

Design Modification 1: Different Window Thicknesses

The baseline model results suggest that the allowable temperature rise for this window is less than 27 K. Since the model overpredicts the tolerance temperature for the parabolic load (as compared to the empirical data), it is reasonable to expect that it also overpredicts the tolerance temperature for the RF temperature load. The expected temperature rise in normal operation is anticipated to be more than 35 K, and some development is necessary in order to arrive at a working window design. The most obvious modification is increasing the window's thickness. This increase will result in two effects: increasing the thermal conductance in the window and increasing the window's stiffness. If the window behaves primarily as a membrane, then the stiffness will increase linearly with thickness; however, if the window experiences significant bending, then the stiffness may increase by as much as the cube of the thickness.

The thermal conductance of the window scales with its thickness, so in order to compare similar power dissipations on windows of different thicknesses, it is necessary to scale the temperature loads by the inverse of the thickness ratios.

For the purposes of this comparison, we analyzed models with three thicknesses: the standard 127 micron (.0050") window, a 190.5 micron (.0075") window, and a 254 micron (.0100") window. Figure 7 shows displacement results for models analyzed with both parabolic and RF (scaled to match maximum temperature rise) temperature distributions. As expected, the RF power distributions caused displacements significantly larger than their parabolic counterparts.

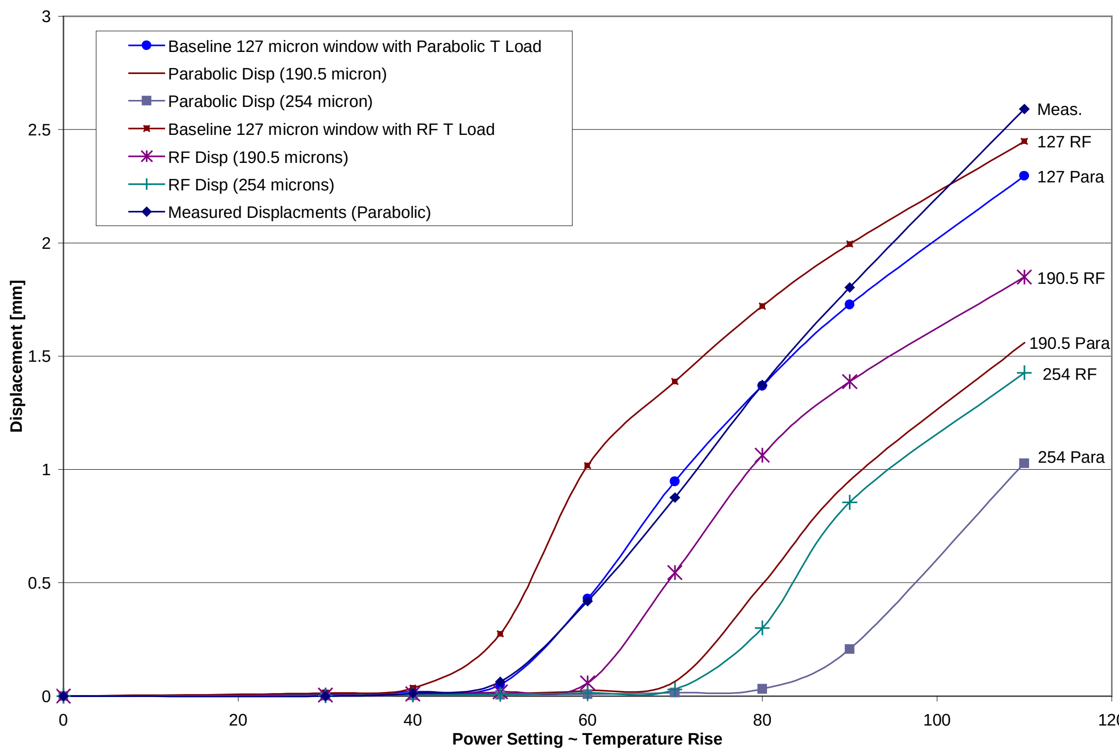

Figure 7. Displacement vs. power setting curves for windows of different thicknesses under RF and parabolic temperature distributions.

Examination of the displacement data allows us to calculate the temperature rises at which the window deflects by the tolerance of 25 microns. These "safe" temperature rises for both the parabolic and RF load cases are shown in Table 2.

Table 2. Safe operating temperature rises for windows of different thicknesses (under RF and parabolic temperature distributions).

Window Thickness [microns]	Temperature for 25 micron displacement underRF load	Temperature for 25 micron displacement under parabolic load
127	27.1	33.1
190.5	27.3	33.9
254	29.9	36.8

It is noticeable that the safe temperature is relatively constant for all of the window cases. This implies that the window acts almost entirely as a membrane - since thermal elongation in the plane of the window causes membrane-type behavior, and planar elongation depends only on temperature rise. It should also be noted that the power setting is not a good indicator of the power dissipated in the window - it is simply an index used to compare similar numbers. For example, a power setting of 80 does not necessarily imply twice the power dissipation of a power setting of 40. (The power setting is actually an indicator of the power consumed in the halogen heating bulb; since the bulb's performance depends on its own temperature and other factors, it does not transmit a constant fraction of its consumed power to the window.) It can also be seen in the table that the 254 micron window appears to have a slightly higher safe temperature than the thinner windows. This may be a real effect due to the fact that the window is thicker (and thus behaving less like a membrane) or it may be an artifact of uncertainties in the calculations. Note again that for a thicker foil to achieve a given temperature rise, the dissipated power is proportional to the window thickness - a thicker foil can dissipate more heat before it deflects significantly.

Design Modification 2: Variable Window Thickness - A "Stepped" Design

While thickening the window has been shown to increase the power dissipated before exceeding the deflection tolerance, it carries with it the disadvantage of increasing muon scattering. This effect is most noticeable at low radius where the muon beam is most dense, and becomes less important at the outer extents of the window. To make use of this effect, we developed a model of a "stepped" window, which is thin in the center, but thicker at the outer radii, as shown in Figure 8. A potential method for fabricating a window of this nature involves chemically etching a constant thickness foil to be thinner in the center [4]. For the purposes of this investigation, it was assumed that the inner thickness would be 127 microns, while the outer thickness would be 254 microns. The step transition radius (the point at which the foil thickens) would be varied from 20 mm to 60 mm. In addition, the window was modeled with a one-sided step, asymmetric about its thickness. The actual foil could be fabricated in either a symmetric or asymmetric fashion.

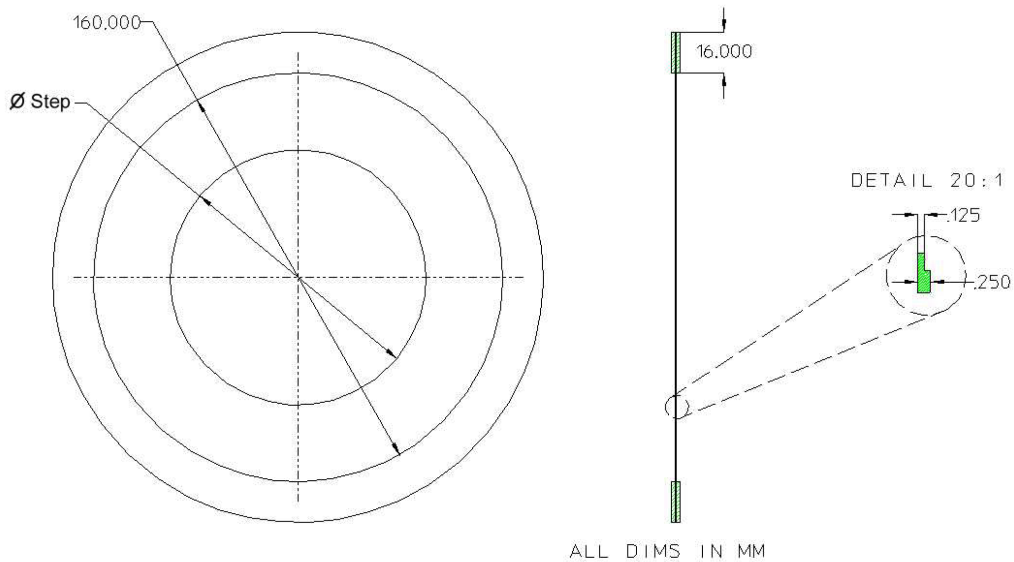

Figure 8. Schematic layout of the step window design showing step diameter and cross section.

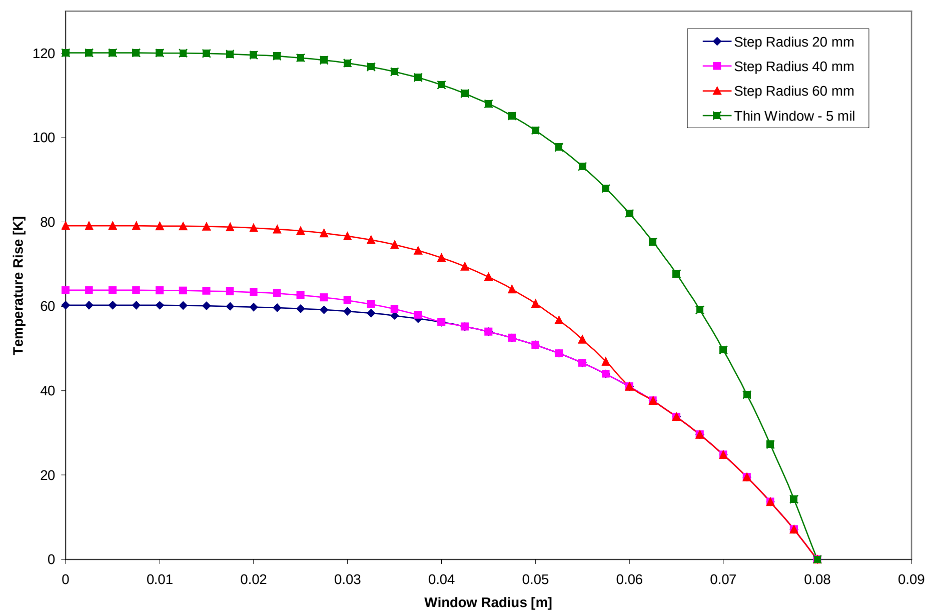

Figure 9. Comparison of step window RF temperature loads to constant thickness window RF temperature loads.

For the stepped window models, only RF temperature distributions were used. The RF temperature profiles computed previously were scaled to account for the thicker sections of the stepped windows. In this way, the total power dissipated in the window is held constant, as compared to other models with RF temperature loads of the same "power setting." Figure 9 shows RF temperature distributions for stepped windows of different step radii, and for a constant thickness window of 127 microns. It is noticeable that adding a step to the window's design significantly reduces the temperature gradient in the window. Adding a step as small as 20 mm wide (i.e. at 60 mm radius) significantly improves the thermal performance. As the step radius decreases, the *relative* advantage of the step becomes smaller.

Figure 10 shows displacement profiles for the stepped window models and the constant thickness window. The stepped window temperature rises at the displacement tolerance of 25 microns are shown in Table 3.

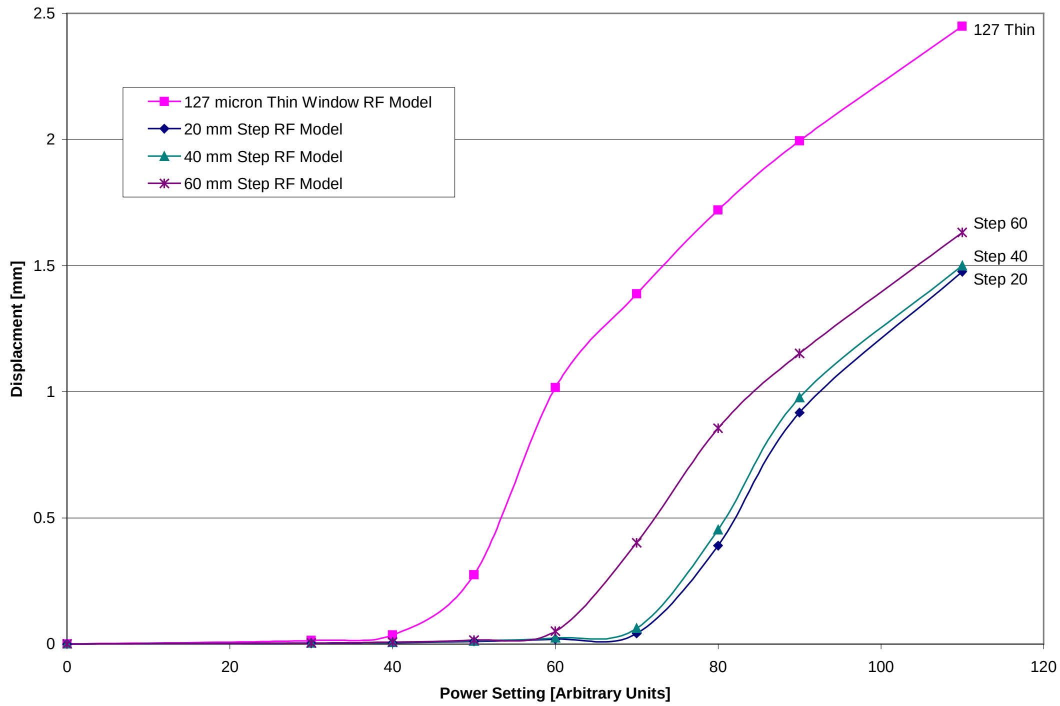

Figure 10. Displacement vs. power setting curves for step windows of different step radii under RF temperature load profiles.

Table 3. Safe operating temperature rises for windows of different step radii (under RF temperature loading only).

Step Radius [mm]	"Safe" Operating Temp Rise [K]
5 mil thin window	27.1
20	28.9
40	26.4
60	28.9

Design Modification 3: The "Ribbed" Window Design

In the event that muon scattering is too high with the stepped window design, it is possible to strengthen the window with a waffle pattern of reinforcing ribs. These ribs not only provide strength to the window, but they also increase conduction to the cooled outer ring, thereby reducing the temperature gradient. In order to produce less scattering than a stepped window, it is important to create a ribbing pattern that covers substantially less area than the step in a stepped window. For the purposes of this analysis, we created a model of a ribbed window with approximately 20% rib area; the thin areas are 125 microns thick, while the ribs are 250 microns thick - see Figure 11.

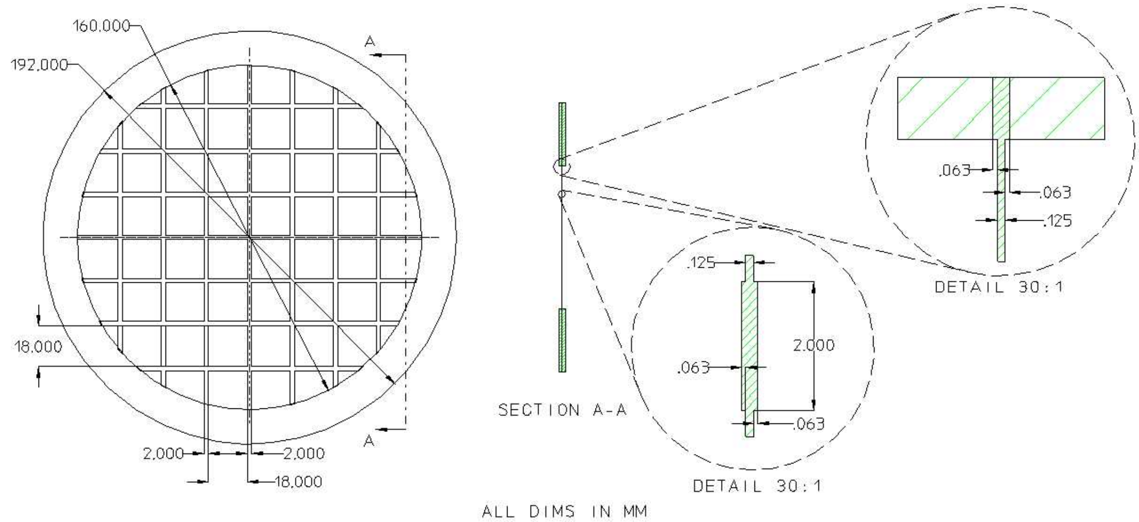

Figure 11. Schematic layout of the ribbed window design.

In contrast to the stepped window designs, the ribbed window contains at least 22% less area of 254 micron foil, see Table 4. While the stepped window was modeled with an asymmetric cross section through the thickness, the ribbed window model was constructed symmetrically. It is proposed to create the waffle pattern by chemically etching a 254 micron foil in the spaces between the ribs, and a vendor has suggested that the window be symmetric through the thickness in order to ease production.

Table 4. Comparison of percentage of window areas above 127 microns thick, for several different models.

Model	% Area @ 254 microns
Ribbed	21.29%
Stepped - radius 60	43.75%
Stepped - radius 40	75.00%
Stepped - radius 20	93.75%

The ribbed window model's lack of axisymmetry makes it impossible to scale temperature loads as in the previous analyses. In addition, the ribs provide thermal conduction as well as stiffening, so the heat flow through them must be taken into account. For these reasons, the ribbed window was analyzed by applying a heat flux load to the model (see Figure 12), in order to generate the temperature profile. This sequence of analyses incorporates one more step than in all of the previous models, and thus demands that we run a comparison model in order to judge how the ribbed model performs. For simplicity, the baseline 127 micron window was chosen as the comparison. This window model was also subjected to RF heat flux loads. In this analysis, both models were subjected to a total heat load of 60 Watts. Contrary to all other models discussed so far, both the ribbed window and the comparison window were created as 90 degree 3d models in order to capture the ribbed window's lack of axisymmetry.

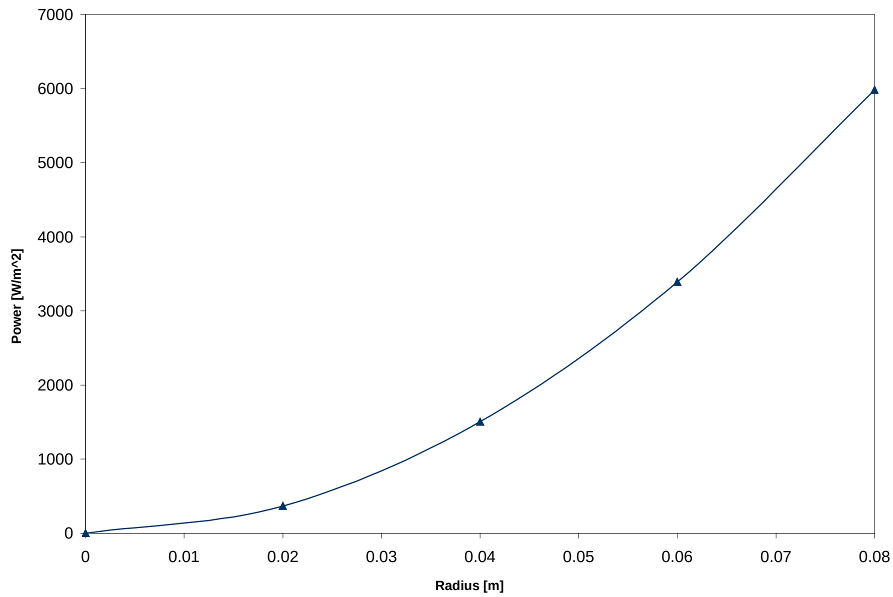

Figure 12. RF heat flux profile used to generate temperature distributions in ribbed window model - total heat load of 60 Watts when applied to both sides of window (30 Watts in above curve alone).

Thermally, the ribbed window performed approximately 12% better than its baseline counterpart, achieving a maximum temperature *rise* of 89 K, versus the baseline window's 104 K (see Figures 13 and 14). Although over 20% of the ribbed window's area has been doubled in thickness, as compared to the baseline, this does not produce a 20% reduction in temperature rise. Most likely, this poor performance is due to the fact that the window's ribs run at 90 degree angles, rather than radially. This arrangement produces a rib conduction path that is approximately sqrt(2) longer than the radial distance between any point and the outer ring, resulting in much of the difference between the 20% area increase and the 12% reduction in temperature rise. Of course, a rib pattern utilizing radial and circumferential ribs is possible, but it encounters the problem of concentrating more thick material at inner radii, unless an unconventional pattern is used. For the purposes of this investigation, only the rectangular waffle pattern was analyzed.

Although structural models were not analyzed, it is expected that the ribbed window would perform slightly better in displacement, due to its lower temperature gradient and the stiffening effect of the ribs. As mentioned earlier, the window behaves largely as a membrane, meaning that the thicker ribs contribute only linearly to window stiffness, rather than to a higher order, as would be observed in a body undergoing beam-type bending. Since the ribs cover 20% of the window's area, and they double the effective thickness in only that area, a decrease of 10% due to structural effects and up to 12% due to thermal effects could be expected. The ribbed and baseline windows are compared in Table 5, which summarizes their maximum temperature rises and expected displacement ratios.

Table 5. Comparison of temperature rises in baseline and ribbed windows.

Model	Temp Rise [K]	Temp Rise Ratio	Expected Displacement Ratios
Baseline	104		1
Ribbed	89	0.85	0.78

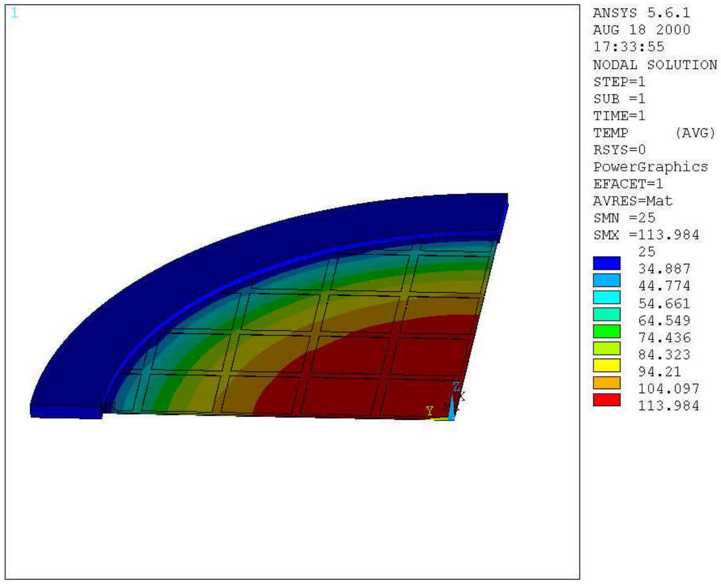

Figure 13. Temperature distribution in ribbed window under 60 W loading - given in degrees Celsius.

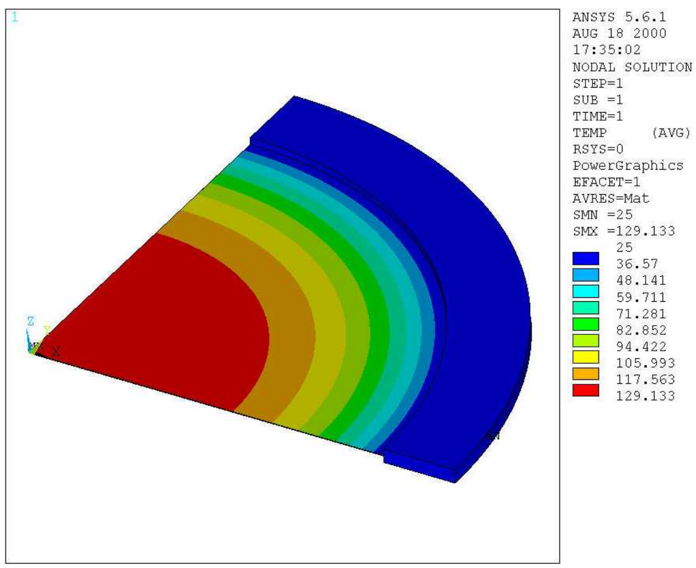

Figure 14. Temperature distribution in thin comparison window under 60 W loading - given in degrees Celsius.

Larger Windows - 38 cm Diameter and Greater

Up to this point, only 800 MHz windows have been examined. The same ANSYS model, however, was changed to model 200 MHz windows of three possible diameters: 38 cm ID, 42 cm ID, and 46 cm ID. The larger windows were also modeled with the same thickness variations explored in the 800 MHz design: 127, 190.5, and 254 microns. The 200 MHz models were subjected to RF power loads (see Figure 12) that were scaled to apply total power dissipations in the range of 0 to 200 Watts total (both sides) - in 10 Watt increments from 0-50 Watts, and 25 Watt increments from 50-200 Watts. In general, displacements were vary large, as shown in Figure 15, which shows displacement versus power dissipation for windows of different thicknesses. Radius changes produced comparable percentage changes in overall displacement, as shown in Figure 16, which plots displacement versus radius for different window thicknesses. The anticipated power dissipation during use is approximately 120 Watts, which corresponds to at least 6 mm of displacement. The maximum power that any of the analyzed windows can dissipate without moving more than 25 microns is approximately 40 Watts, which corresponds to a temperature rise of 34 K across the window. Interestingly, this temperature rise is slightly higher than the corresponding "safe" temperature rise found for the 800 MHz window (~28 K). Since the window exceeds its operational tolerance (25 microns) by a factor of over 200, stepped and ribbed designs, which improve performance by less than a factor of two, were not considered.

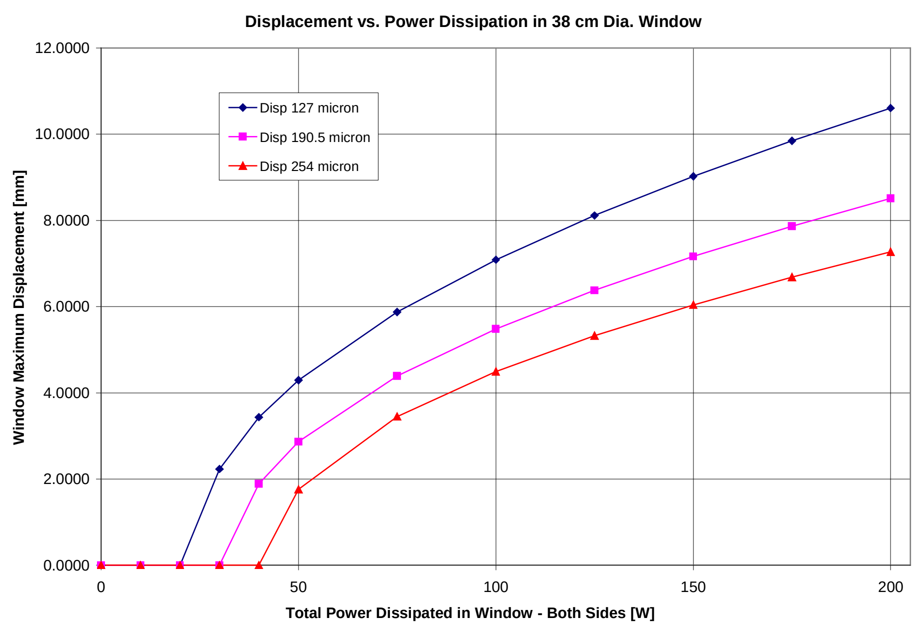

Figure 15. Displacement vs. power dissipation for large windows of different thicknesses.

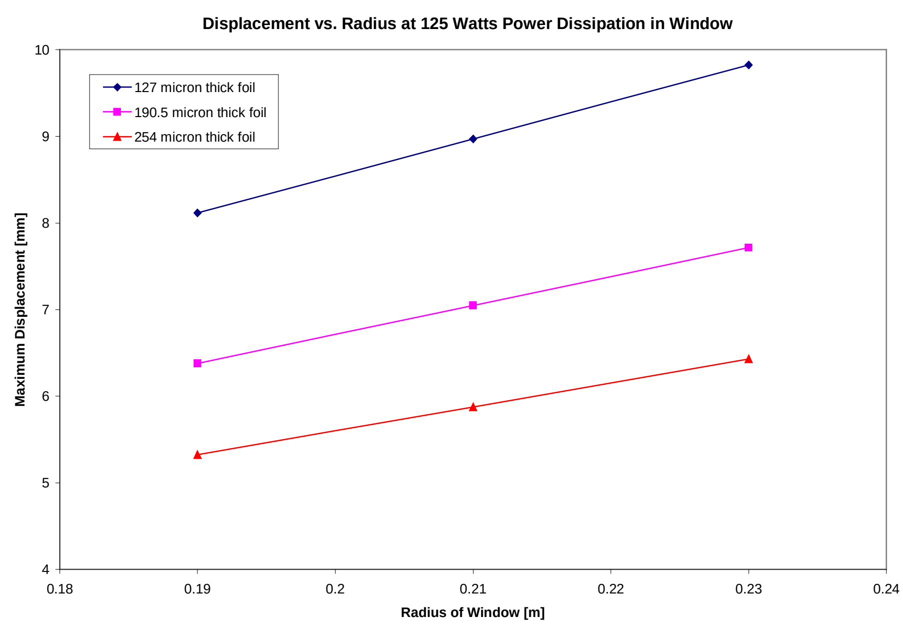

Figure 16. Displacement vs. radius for large windows of different thicknesses, all under 125 W total power dissipation.

Conclusions

FEA analysis suggests that a uniform thickness beryllium window of 16 cm diameter will allow operation at temperature rises up to 27K with displacements of less than 25 microns. Increasing the window's thickness to 254 microns would allow it to absorb enough power for the RF cavity to remain on tune at the expected RF power dissipation. Scattering in a 254 micron foil has not been calculated, however.

Another design for the small window, with the possibility of reduced overall muon scattering, is to produce a stepped window with a doubled-thickness section beginning at approximately 6 cm radius. The temperature rise in such a window would be expected to be only two-thirds of the uniform, thin window, resulting in 33% higher power capability.

A ribbed window, only 20% better than the uniform thickness baseline, possesses less than half the "thick" area of a stepped window. Once again, however, scattering from a ribbed window has not been analyzed.

The analysis shows, however, that operation of a larger window (38 cm diameter) will not occur within tolerance at temperature rises above 34 K, which amounts to 40 W dissipated in the foil. At a reasonable expected power loss, approximately 120 Watts, the displacement is so high (> 6 mm), that the stepped and ribbed designs mentioned beforehand have no possibility of bringing the window within tolerance.

These results encourage further development of 800 MHz window designs, in particular prototyping and testing in an RF test cavity. However, they also show that for 200 MHz operation, radical design changes will be necessary for windows to operate effectively.

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