Comparison of Deflection Measurements to FEA Modeling for Muon Cooling Channel RF Cavity Windows

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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 805 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. Since the beryllium windows that are to be used in the cooling channel are brazed, they are under some amount of pre-stress. This stress makes validation of the FEA model difficult, so aluminum windows of the same size and shape were created with no pre-stress. These windows were tested with a halogen bulb that created a temperature distribution similar to that derived from RF heating. Deflection measurements from the aluminum test windows were compared to those for analagous FEA models. In general, agreement between model and physical test was good, with deflection measurements falling within 10% of those predicted by FEA.

Introduction

The Beryllium windows for the Muon Cooling Channel consist of 127 micron, 16 cm diameter foils of high purity Be. These window assemblies are used in a chain of interleaved RF cavities, where the RF frequency is highly dependent on the flatness of the window. Since the windows undergo significant ohmic heating, and this heating causes deflection, it is critical that the deflection is compensated for in some manner.

In order to determine the sensitivity of the windows to heating, two Beryllium test windows were fabricated and tested by heating with a halogen bulb. Each foil is brazed between two annular rings of lower purity Be, each 16 cm ID, with an annulus of 16 mm; the rings are each approximately 1.6 mm thick. 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 [1,2]. 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.

One key goal of the window testing was to correlate the empirical test data with an ANSYS finite element model. Once a good FEA model was created, this model could be used to investigate the amount of pre-stress present in the window, and to determine how much heating this pre-stress would allow before the window would deflect. In order to validate the FEA model, however, we needed empirical 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 or diffusion bonded, however, this Al window was bolted together, in order to insure that no pre-stress would be included. A layout of the aluminum test window is shown in Figure 1.

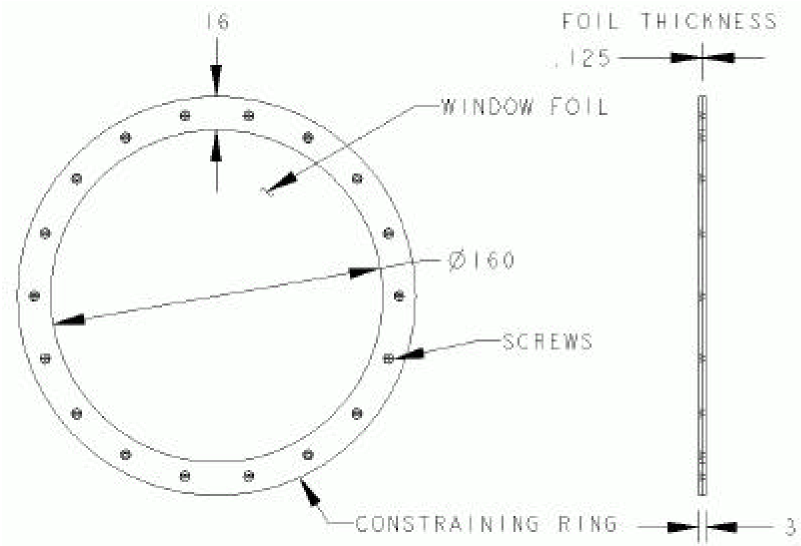

Figure 1. Layout of aluminum test window created to match Beryllium window dimensions (all dimensions in mm).

Experimental Setup

Two different test setups were used. In the first setup, the windows were heated with a halogen bulb in a temperature controlled enclosure. Displacement was recorded as a function of foil radius, while the temperature was recorded with an infrared camera [1]. In the second test setup, the windows were installed in a low power RF cavity, with a halogen bulb suspended in the cavity's center [2]. Temperature and displacement were then measured for different values of power dissipated in the halogen bulb. This setup more closely modeled the radiative heating conditions that the window would be subjected to in an enclosed space. In addition, the windows were tested with their outer rings both bolted and free, in order to determine what effect the edge constraints on the window have. The experimental setup for the second test is shown in Figure 2.

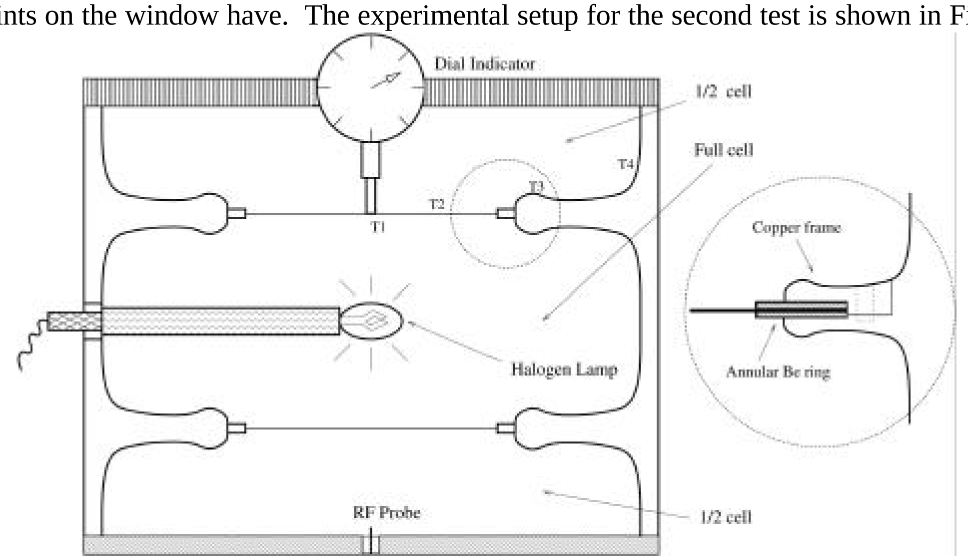

Figure 2. Experimental schematic for window testing conducted in prototype RF cavity. (Thermocouples labeled T#, displacement dial on top window.)[2]

In the second test setup, displacement measurements were made with a dial gauge mounted on the upper window, while thermocouples were placed at three locations on either the bottom or top window: at center, at the mid-radius, and at the edge of the ring. It should be noted that the displacement measurements were taken only at the center of the window, and reflected only the maximum values of the displacement. The temperature and displacement measurements were made on different windows to avoid dial gauge and thermocouple overlap at the window's center. Due to the symmetry of the cavity it was deemed that this was an acceptably accurate solution. The aluminum windows were also coated with a thin layer of high emissivity "spray paint" in order to maximize their heat absorption. The halogen bulb was connected to a variable voltage supply, which was changed in order to take several different temperature and displacement readings.

FEA Model

The goal of testing the aluminum windows was to validate an FEA model of the window without any bonding pre-stress. A simple, 2D axisymmetric model was created in ANSYS, and the temperature distributions measured in the experimental data were applied as temperature loads. From these loads a displacement profile was calculated, and this profile (or its maximum) was compared to the empirically measured displacement. A schematic of the model, with characteristic loads, is shown in Figure 3. The material used was 6061-T6 aluminum, modeled with a CTE of 22.3 ppm/K, and a Young's modulus of 70 GigaPascals. The FEA model consisted of all quadrilateral elements, with three elements through the thickness of the foil, and a total of 930 elements, 1200 nodes in the entire model.

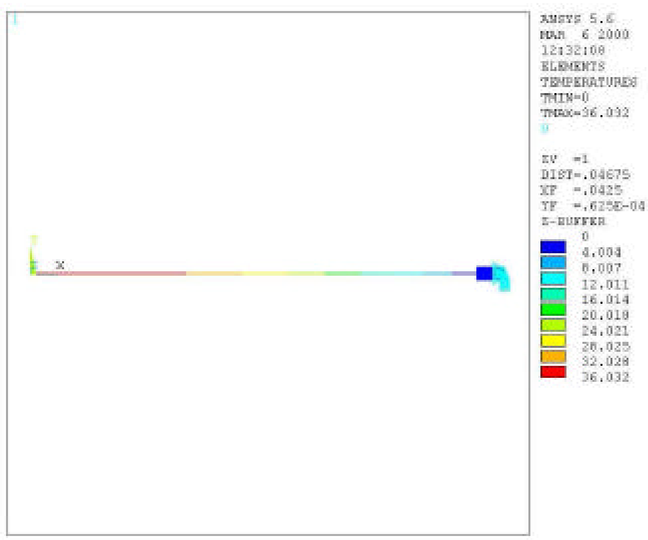

Figure 3. FEA model of window showing constraints on the ring (small triangles) with temperature load shown as contours. Window axis is denoted by the Y axis of coordinate system.

The temperature information collected from the window measurements consisted of two types of data. From the first experimental setup, using the thermal imaging camera, temperature curves were obtained for the window as a function of radius. These curves were then normalized to the ring temperature, and fitted with a quadratic function, which was used to apply loads in ANSYS as a function of position. In the second experimental setup, only three temperature data points were taken. In order to make up for this lack of data, these points were also fitted with quadratic functions, and these functions were applied as loads in the same way as the first case. The thermal load data is shown below in Figures 4 and 5 for the first and second experimental setups, respectively.

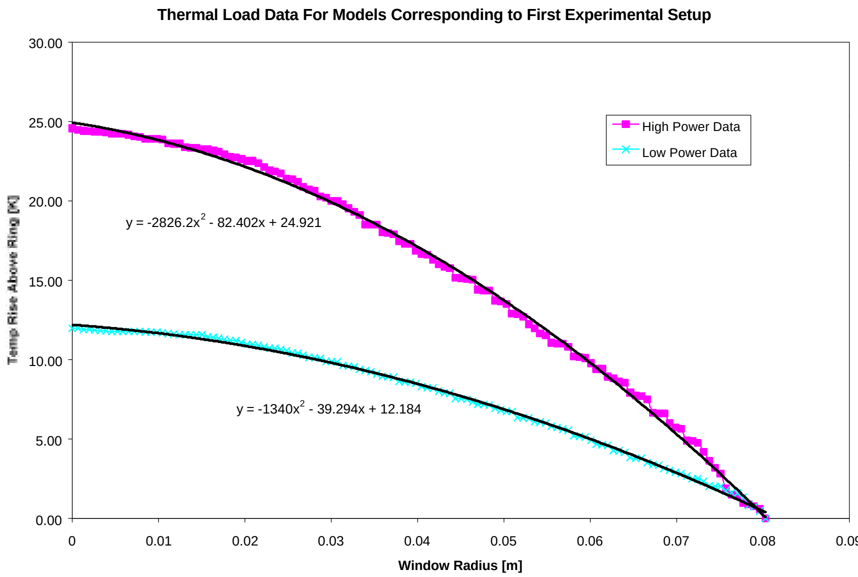

Figure 4. Temperature inputs for FEA model as derived from first experimental setup (using thermal imaging camera). Note that two tests were performed using two different power settings on the halogen bulb that was used to heat the window.

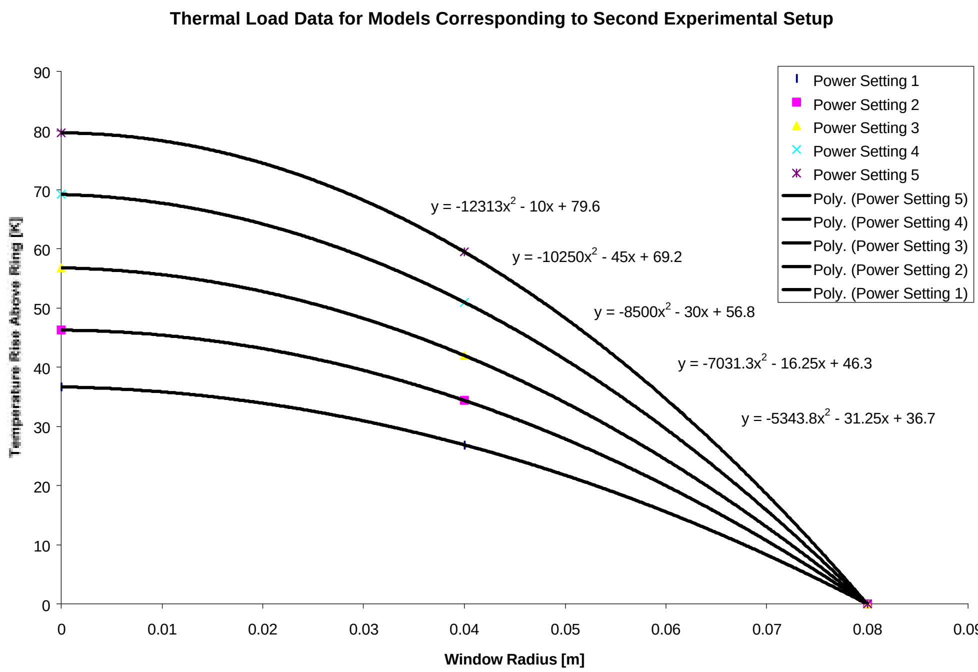

Figure 5. Temperature loads for FEA model as derived from second experimental setup (using prototype RF cavity). Note that five tests were performed using different power settings on the halogen bulb that was used to heat the window.

The constraint conditions applied in the FEA models (as shown in Figure 3) fell into two categories: complete constraints on the rings (i.e. the rings were constrained both radially and vertically) and partial constraints (i.e. the rings were constrained only in the vertical). Since the model is axisymmetric, the partially constrained case amounts to the window sitting on a flat surface. For the first experimental setup, the window was essentially only partially constrained, since it was held to its measuring fixture with large paper clips. It should be noted, however, that although the window was only partially constrained structurally, it was actively cooled around its perimeter during the test [1]. In the second experimental setup, the window could be constrained in all directions by a bolted copper ring mounted in the cavity. In one set of measurements, the window was fully clamped; these measurements were then repeated with the copper ring unbolted and removed, but the window still sitting in the cavity. In order to compare constraint conditions to the FEA model, the model was analyzed using both constraint conditions (complete and partial).

Results and Discussion

A contour plot of one of the FEA models is shown in Figure 6 in order to provide a visual reference as to what orders of deflection were observed. All of the results are qualitatively similar to the plot shown here.

As stated earlier, the FEA models were analyzed by comparing their displacement results to the measured displacements. In the case of the first experimental setup, these measured displacements were available as a function of radius, while for the second setup only the maximum deflection was measured.

The results for the first experimental run are shown in Figure 7. It can be seen that while absolute agreement between experiment and model is poor (approximately 33% at maximum displacement), the relative agreement between "high" and "low" power measurements is good. In fact, the ratio between these two maximum deflections in the FEA model (0.68) differs from the

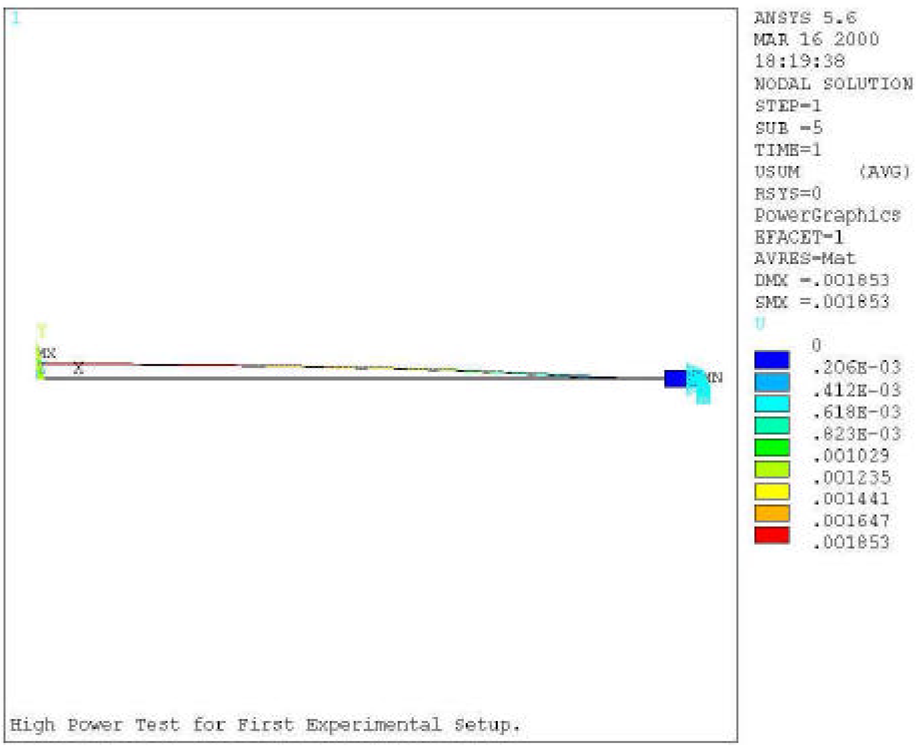

Figure 6. FEA model showing contoured displacement plot for the "high" power run in the first experimental setup (note that deflections are real size and that undeformed edge is shown for comparison).

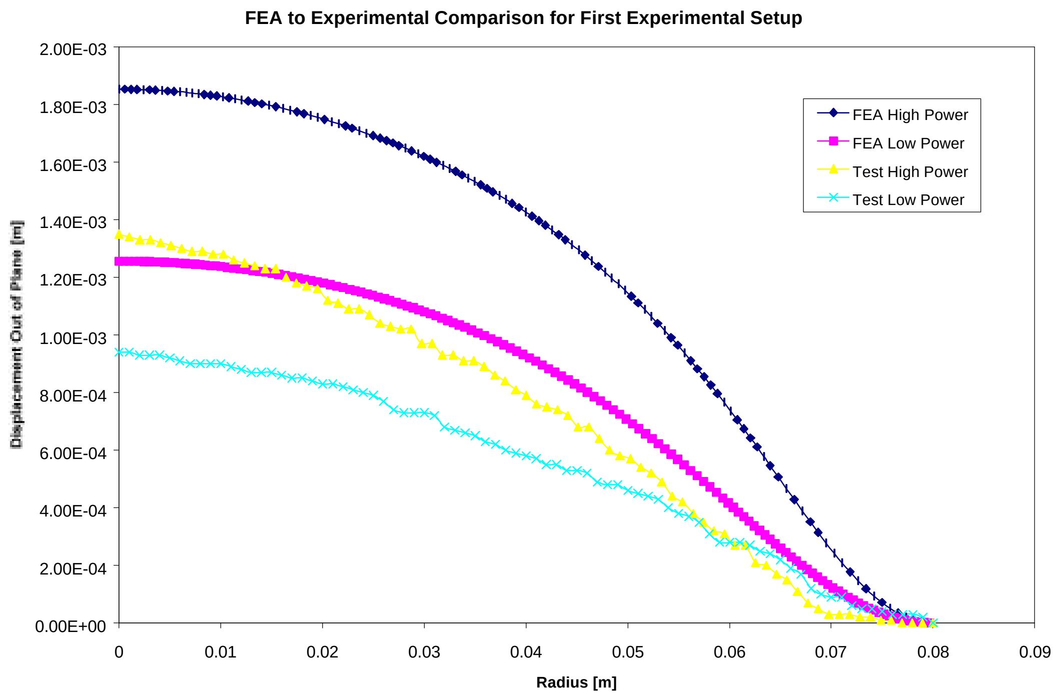

Figure 7. FEA results compared to experimental results for first experimental setup.

measured deflection ratio (0.69) by only 2%. This result indicates that the model's physical behavior is close to reality, but that for some reason there is an amplitude offset in the numerical result. One possibility for this error is an inaccuracy in the thermal imaging system, or in the electronic displacement gage that was used during the experiment. Both of these instruments require some degree of calibration, which could explain some of the discrepancy between model and experiment. It can also be noticed that the measured and calculated displacement shapes are somewhat different qualitatively; in particular, the measured shapes show a finite (rather than zero) slope at the center of the window. Part of this discrepancy can be explained by the displacement gauge, which introduces a spring force on the window with its measurement tip. This force creates a displacement in the window which increases with decreasing radius, meaning that the measurements near the center of the window are exaggerated, while those at the periphery are closer to their actual values. Accounting for the displacement induced by the measurement apparatus would yield a curve with a flatter profile on top, qualitatively similar to that derived from FEA analysis. The displacements due to the measurement gauge are small (on the order of 1/10th of a millimeter) so they explain why displacement shape may be different, but not why the overall values differ by so much.

Results from the second experimental setup compare much more favorably with the FEA models. Table 1 shows the maximum displacements for all five tests conducted in the RF cavity, along with their corresponding FEA values. Agreement between model and experiment is good here, both qualitatively and quantitatively, giving good confidence that the FEA model is valuable as a predictive tool in analyzing window deflections. It should also be noted that the difference between complete and partial constraints in the FEA model is small (approximately 1%), indicating that the method of window attachment is not critical in determining overall deflection. (This result is consistent with conclusions in the paper by D. Li [2]).

Table 1. FEA results compared to experimental results for second test setup.

Power Level	Measured Disp. [mm] Complete Constraints	FEA Displacement [mm] Complete Constraints	FEA Displacement [mm] Partial Constraints	Difference (Com./Par.)
1	2.03	2.23	2.195	8.7% / 8.0%
2	2.35	2.52	2.489	6.6% / 5.9%
3	2.64	2.78	2.758	5.1% / 4.4%
4	2.93	3.07	3.046	4.4% / 3.8%
5	3.20	3.31	3.293	3.4% / 2.9%

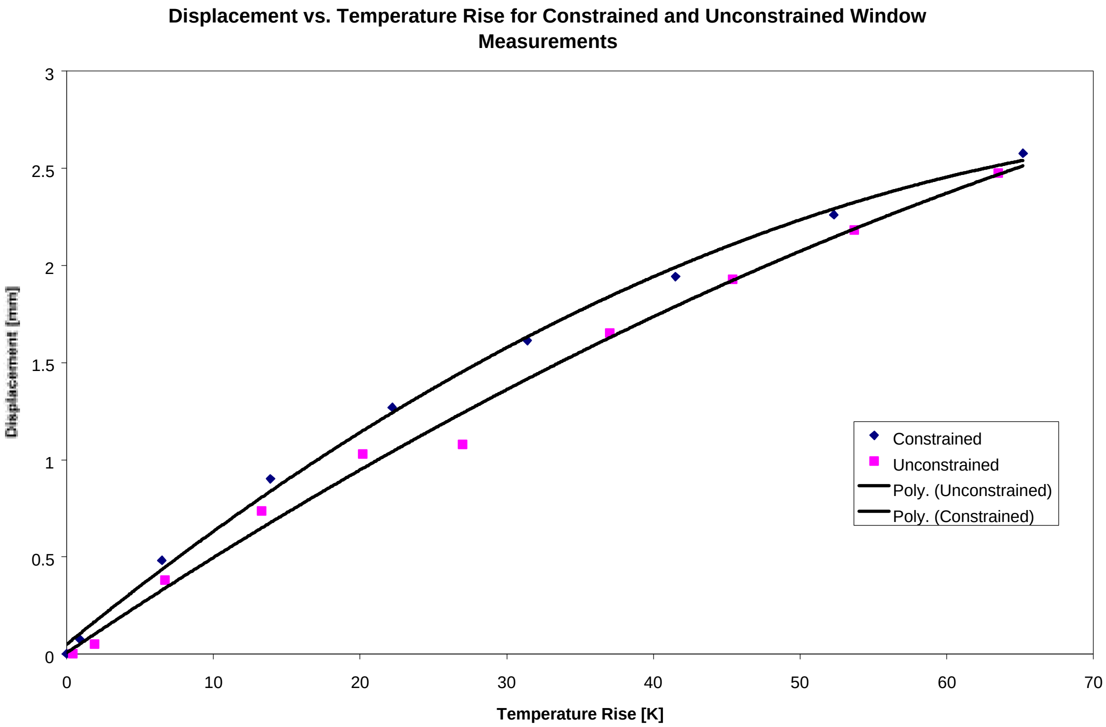

Figure 8. Displacement measurements plotted versus window temperature rise (center to ring) for constrained and unconstrained models tested in the mock RF cavity.

Comparing complete to partial constraints, however, is not as straightforward in the real world as it is in the FEA model. The reason for this discrepancy is that in the real world, the temperature distribution for any given power setting changes depending on whether or not the window is fully constrained. This is explained by the fact that the window sits in a large copper cavity of high thermal conductivity and thermal mass. When the window is bolted in place, it becomes better thermally coupled to the cavity, and the temperature rise on the window decreases. In order to compare the effect of mechanical coupling to the cavity on displacement (without being confused by the thermal coupling) the displacement results for different temperature rises were plotted based on whether or not the window was fully constrained (see Figure 8). It can be easily seen that the constrained window showed larger deflections on average for the same temperature distributions across the window. In addition, the difference was similar to FEA prediction, although greater on average (about 10%).

One last effect observed during the testing was that the temperature rise on the window is due almost entirely to the thermal resistance of the thin foil. This fact was observed when the temperature distributions measured for the free window showed similar shape to those measured for the constrained window. As expected, the constrained window showed a lower maximum temperature (by about 10%) but the temperature rise (ring to center) was identical, and the shape of the distribution negligably different.

Conclusions and Future Plans

Qualitatively, the window behaved identically in practice and theory. Heating of the thin foil caused significant out of plane deflection, which was noticeable to the naked eye (more than 1 mm). All deflections were elastic in nature, and the results were very repeatable, although this fact is not quantified in this paper.

Overall, the experimental window testing has demonstrated two things: first, that the unstressed model corresponds well to measured values; and second, that large window displacements may be reasonably expected for non-stressed simple foils (with no compensating mechanism). It was also observed that the direction of displacement of a flat window is indeed an instability; each of the tested windows would bow in either direction, depending on which way the window was pushed initially. It was also seen that this direction could be reversed simply by forcing the window back to the other side. This result suggests that pre-bowing the windows will pre-determine them to move in one direction, and the approach of using a series of pre-bowed windows appears to be possible in order to compensate for the possibly large deflections. We will be investigating both pre-bowed windows and ways to control pre-stress in the near future, analytically and experimentally.

References

[1] "Deflection Measurements of thin foils for the muon cooling channel RF cavities." J. Corlett et al, MUCOOL 62, CBP Tech. Note 194, Lawrence Berkeley National Lab, Berkeley, CA, 1999.

[2] "Be Window Studies at Room Temperature." D. Li et al, MUCOOL 110. Lawrence Berkeley National Lab, Berkeley, CA, 2000.