Be Window Studies at Room Temperature

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Abstract

We report recent experimental studies on the mechanical properties of Be windows in 805 MHz $\frac{\pi}{2}$ interleaved RF cavities (cool-test model) for muon cooling experiment at Fermilab. These windows are 127 μm thick, pre-stressed flat disc beryllium foils with 16 cm diameter. Each foil is sandwiched into two 1.6 mm thick and 1.6 cm (8 cm $\in R \in$ 9.6 cm) wide annular beryllium frame by diffusion bonding. A halogen lamp was used to heat and produce a temperature distribution on the windows similar to that generated by RF power heating. Three Type-T thermocouples were attached to one side of the window surface to measure temperature variations of the window as a function of the heating power. For a comparison, two non-stressed aluminum windows with the same dimensions were fabricated and tested.

1 Introduction

In order to compensate longitudinal energy of muon beams lost in a cooling channel and provide necessary longitudinal focusing force, a high gradient RF accelerating structure is required to minimize the length of the cooling channel. For muon beams

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at energy of 220 MeV (lifetime $\sim$ 4 μs), the cooling channel calls for an energy compensation at the level of 13 $\sim$ 14 MeV/m, which requires a RF structure to have an accelerating gradient at the order of 30 MV/m at 805 MHz. To produce such a high field, a conventional structure would have to operate at the peak surface field around 90 MV/m or more, which is three times of the Kilpatrick limit. By taking advantage of the penetration property of muon beams, an interleaved $\frac{\pi}{2}$ RF cavity structure [1, 2] was proposed, where conventional beam iris in a RF cavity is covered by thin metal foils of low Z material, which allows cavities to be interleaved and the on-axis accelerating fields to be enhanced further. The cavity geometry then resembles closely to a cylindrical pill-box cavity. RF coupling between cavities is accomplished by coaxial type side-couplers through an open slot on the side wall of each cavity. To increase acceleration efficiency further, two chains of such structure are interleaved and operated at $\frac{\pi}{2}$ mode, thus a higher transit time factor is obtained (see Figure 1). Beryllium has been chosen as the low Z material for the windows due

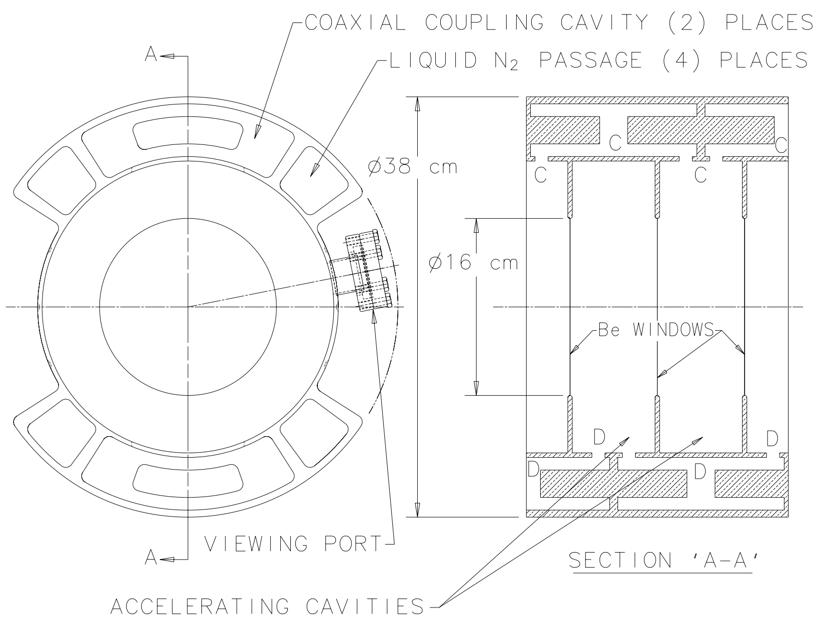

Figure 1: An $\frac{\pi}{2}$ interleaved RF structure with thin Be windows and coaxial type side-couplers. The structure is designed to be resonating at 805 MHz and used in muon cooling channels.

to its low electrical resistivity and high thermal conductivity. Beryllium is a metal which has the lowest ratio of stiffness to weight. Literatures show that beryllium has better electrical and thermal conductivity than that of copper at LN_2 temperature [3], which implies that a copper structure with beryllium windows, its quality factor, Q value should be doubled by operating it at LN_2 temperature.[1] Consequently, to provide the same acceleration voltage, the required peak RF power for this structure will be reduced by a factor of two. Nevertheless, the structure still has to be operated at the same very high fields. For successful operation it is essential to be assured that the Be windows in each cavity can hold such high *EM* fields and be kept as flat as possible so that the resonant frequency is not detuned by the deformation of the thin Be windows. To keep each cavity having the same resonant frequency is important for any resonator-coupled structure, such as the interleave one, in order to maintain the designed field distribution and coupling between cavities and RF source. RF power dissipation on the windows (in the form of ohmic loss) will heat and cause the windows to deform. The deformation may come from different thermal expansion coefficients between copper and beryllium, temperature gradient on the windows due to finite thermal conduction. Furthermore we found that the reported beryllium's electrical and thermal properties increase dramatically its purity at low temperature. Studies on properties of commercial grade beryllium becomes critical for modeling such a structure for engineering design.

Based on commerical available beryllium and information, experimental and theoretical works have been conducted within the MUCOOL collaboration to measure the electrical conductivity at both DC and RF frequency, and estimate temperature distributions and displacement of the windows due to the RF heating power [3, 4, 6, 5, 7]. A cool test copper cavity model, which consists of two half and one full accelerating cells, as shown in Figure 2, was designed and constructed to study many of these concerned issues experimentally. The Be windows used in the cool-test model are made from 99.8 % pure beryllium by Brush Wellman Inc., a company specialized in beryllium products in Fremont, California. Each window is 127 μm thick, 16 cm diameter circular disc, and has been pre-stressed and sandwiched into two 1.6 mm thick and 16 mm wide less purity beryllium annular frame (8 cm $\in R \in$ 9.6 cm) by diffusion bonding. Measurements conducted earlier have confirmed that the measured Q value of the cool test model has been nearly doubled at LN_2 temperature. The measurement results is shown in Figure 3. Due to the nature of a bolted structure of the cool test model, RF power dissipation on surface joints could have dominated the measured Q values. Precautions have been taken to reduce this power dissipation by

[1] Resistivity reported in literature (in the unit of $\mu\Omega$-cm): Cu 1.72 (room temperature) and 0.21 (LN_2 temperature); Be 3.76 (room temperature) and 0.075 (LN_2 temperature)

Figure 2: Cool-test copper model of the 805 MHz $\frac{\pi}{2}$ interleaved RF structure with a coaxial type side coupler. The Be windows used to cover 16 cm diameter beam iris do not show in this picture. The inner conductors of the side-coupler, cavity cells and end plates are bolted together.

putting spring seals, flattening end-plates and applying uniform torque force at each bolt. The Q values have indeed been improved and repeatable, but we believe that the real Q should be much higher than what we have measured.

RF power dissipation on the Be windows contributes less than 15 % of the total power losses on the cavity assuming perfect RF contacts. The measured Q values of the cool test model are not precise enough to deduce quantitative information on the electrical conductivity of beryllium at low temperatures.

Thermal conductivity and thermal expansion play a key role on the deformation of the thin Be windows at high power RF operation. A good cavity design relies heavily on these thermal properties, and should be able to efficiently conduct the heating power out of the thin windows to reduce the temperature gradient so that the a proper engineering design can be employed to accommodate (control or reduce) the thermal expansions. It seems that the best and simplest way (may be the only way) is to apply (without affecting muon beams) enough cooling around the periphery of the windows. The efficiency of the heat conduction depends mainly on the window thickness and its thermal conductivity which is a temperature dependent parameter.

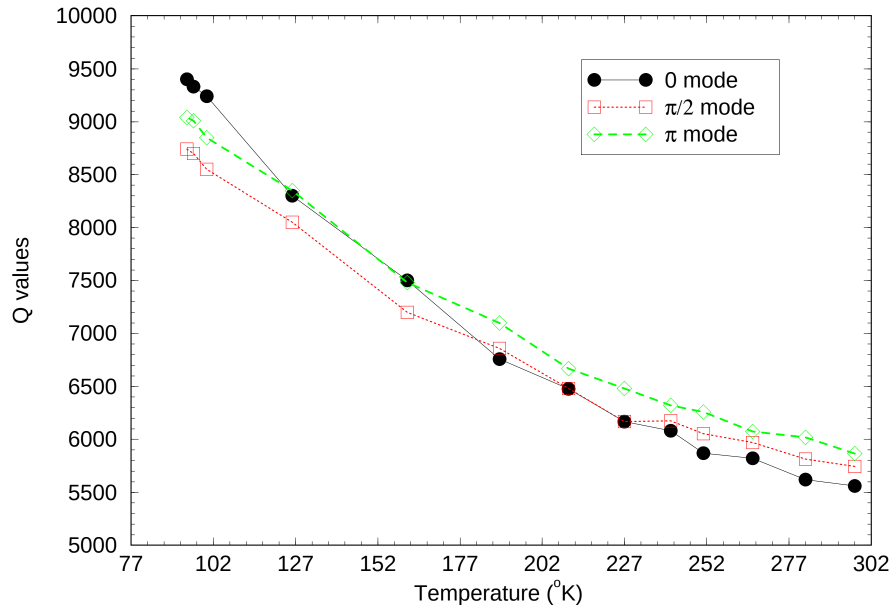

Figure 3: Q values of different modes of the cool-test model are plotted as a function of temperature. Three modes, 0, $\frac{\pi}{2}$ and π were excited and detected from coupling holes at the center of end-plates. Q values were measured from S_{21} using a network analyzer.

The temperature rise (we define it as the temperature difference between the center and the frame of the window) depends on average power dissipation on the window as well. The window displacement increases with the temperature rise and gradient.

Based on Be thermal coefficients at room temperature, the temperature distribution and displacement of the windows due to the presence of the RF heating have been studied theoretically [6, 7]. Numerical simulations have been carried out as well by N. Hartman at LBNL [5]. To validate the theoretical and numerical model, experimental studies are necessary. Ideally, to simulate and test the window displacement requires using high power RF source to generate the needed temperature distribution, which is expensive and impractical for the cool test model. On the other hand, if a similar temperature distribution can be achieved by other means, a sensible experimental study still can be conducted. We found that the temperature distribution on the thin windows heated by a halogen lamp produces similar distribution to that generated by RF heating. An experimental study on Be windows has been reported earlier in [8] where a halogen lamp was used as the heating source. This note reports further experimental studies on these windows at room temperature using the same halogen lamp heat technique, but with the windows mounted in the cavities, and with higher heating power.

2 Measurement Setup

The experiment layout is shown in Figure 4. Temperature was measured across the

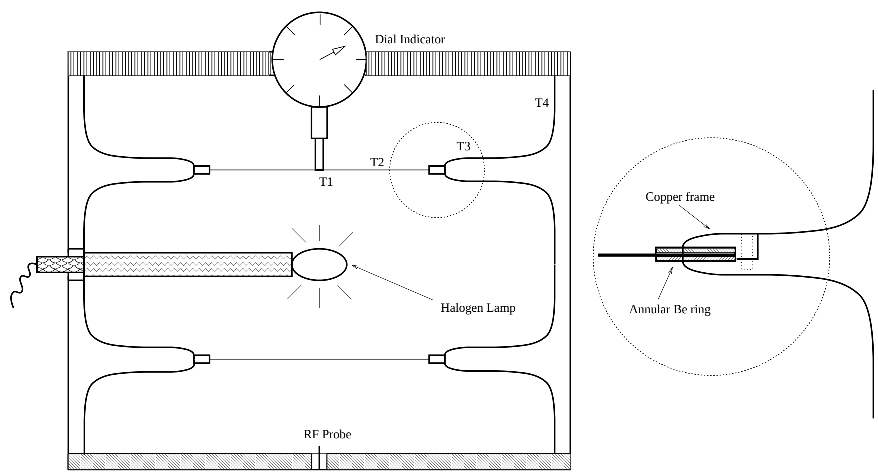

Figure 4: Experiment layout of beryllium window studies at room temperature.

radius R at three points of the window under test (WUT). Three Type-T thermocouples, T_1, T_2 and T_3 are positioned at locations of the center, half the radius ($\frac{R}{2}$) of the window and the annular beryllium/aluminum frame, respectively. They are fastened to contact directly to the surface of the window. Each thermocouple is soldered to a 0.5 cm diameter copper foil and fastened to the test point by copper tape. The window displacement was measured at the center of the WUT using a mechanical dial indicator which is grasped by a brass holder to keep it staying fixed on top of the cavity body, as shown in Figure 5. The indicator has full travel-range of 12.7 mm with resolution of 0.0064 mm. A halogen lamp, which outputs as high as 100 watts at 12 volts, is attached to a lamp holder, which is designed and manufactured on site with an aluminum tube attached to allow electricity wires to go through. The halogen lamp was suspended and positioned to be in the center of the center cavity so that the same temperature profile on both the upper and lower windows can be achieved. To reveal more details of the experimental layout, another photo is shown in Figure 6 where the halogen lamp and a non-painted beryllium window can be seen. The input power of the halogen lamp was controlled using a variable voltage

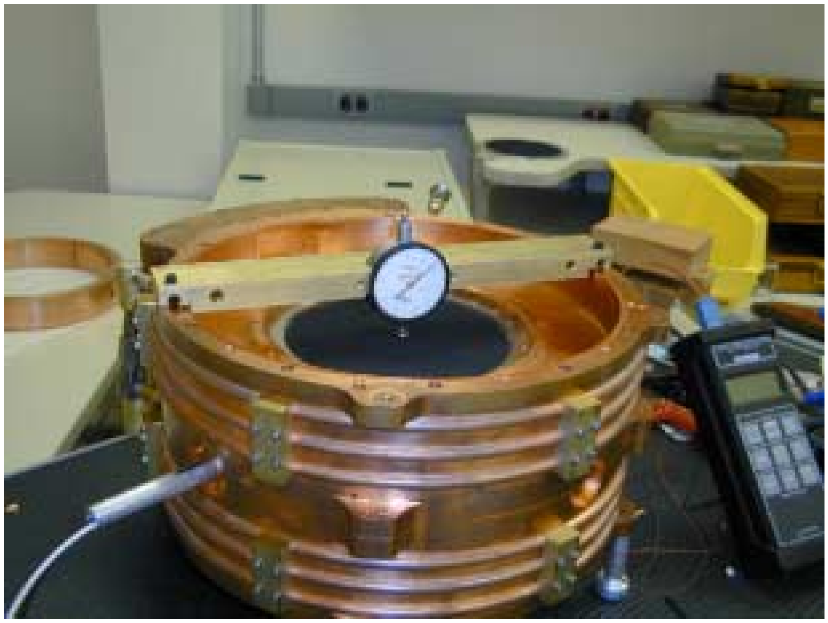

Figure 5: This photo shows the experimental setup of the window displacement measurement. The window shown in this photo is an aluminum one with a black paint on the upper surface. The dial indicator and the brass holder can also be seen. At the right bottom conner is a thermometer used for temperature measurements.

transformer which allows the input voltage of the lamp to be adjustable between 0 and 12 volts (corresponding to power input from 0 to 100 watts). A microprocessor thermometer, made by ΩOMEGA company, was used for temperature readings.

The input power of the halogen lamp was first calibrated against the output of the variable voltage transformer. The displacement, temperature and frequency measurements were conducted and recorded as a function of heating powers.

3 Measurement Results

Measurements were carried out for two different types of windows: non-stressed aluminum and pre-stressed beryllium windows. The windows were installed in the cool-test model of the $\frac{\pi}{2}$ interleave cavities. The halogen lamp was powered to generate temperature distribution on the windows. The heating power of the lamp was adjusted from 0 to its full output power of 100 watts. For all the measurements, both

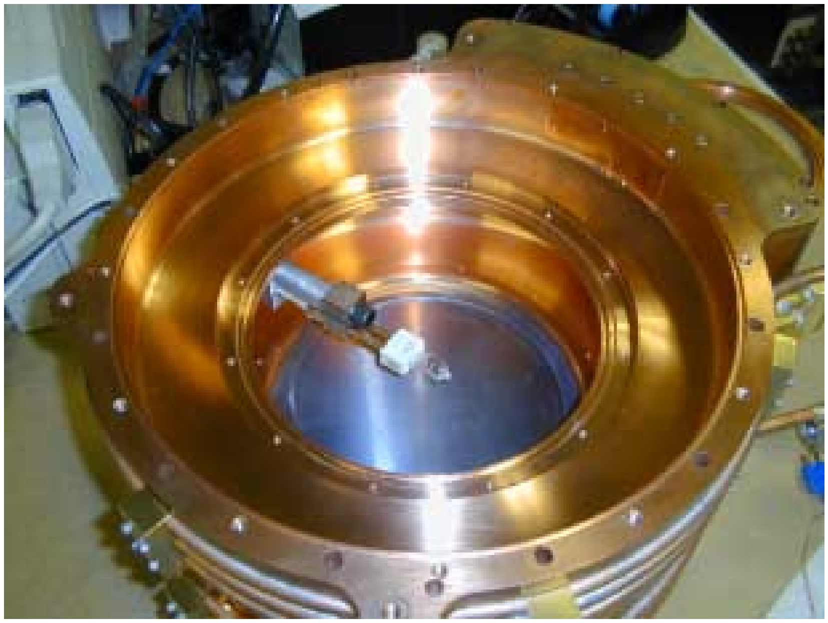

Figure 6: This photo shows the measurement setup with the upper window being taken off. The halogen lamp and its holder can be viewed clearly. A beryllium window without black paint (under the lamp) can also be seen.

the inner surfaces of the upper and lower windows have black paints [2] (facing the halogen lamp) for better heat absorption.

3.1 Temperature rise

Temperature rise is defined as the temperature difference between the center and the annular frame of the WUT, T_1-T_3. The temperature rise was recorded and plotted at different heating powers, as shown in Figure 7. To study the effect of the edge constraints (boundary conditions for analytical and numerical model) on the window displacements, the measurements were performed for cases with and without edge constraints where the outer annular copper frame was either bolted tightly or loose to allow the WUT to be expanded freely. Detailed measurement result are listed in tables in appendix. As indicated in Figure 7, the temperature rise with the edge constraint is noticeable higher than that of the non-edge constraint case. This is because the edge constraint gave better thermal contacts between the WUT and the copper cavity body, which in first order approximation is a constant low temperature

[2] The same beryllium and aluminum window were used for the measurements reported in [8].

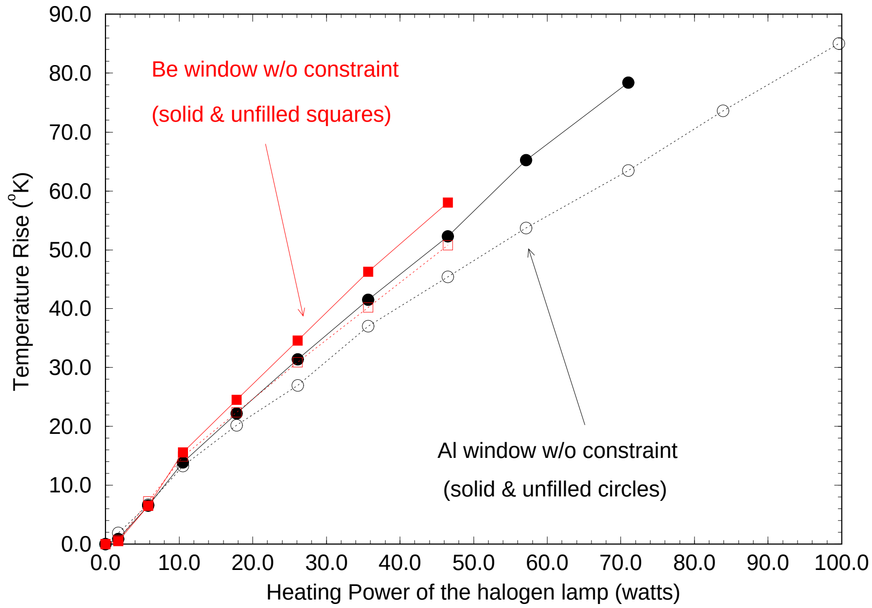

Figure 7: The temperature rises of Be and Al windows are plotted as a function of the heating powers. Windows with or without the edge constraints were tested.

reservoir. Therefore the temperature on the ring of WUT, T_3 is lower and T_1-T_3 is higher (see tables in appendix). In both cases, the temperature rise appears to be linearly increased with the heating power as predicted in theory [6], but with different slopes which imply that the Be window has slightly lower thermal conductivity than aluminum.

3.2 Window Displacement Measurements

The displacements were measured using the dial indicator at the center of the WUT. Due to the spring loading force (initial conditions) of the indicator, the displacements happened to be always in downward direction. We believe that it could go either way if there is no such an initial perturbation. Figure 8 shows the displacement measurements plotted against the heating power. As a comparison and serving as a bench mark measurement for validating the ANSYS numerical model which N. Hartman has been working on, non-stressed aluminum windows were measured and plotted in Figure 8 as well. The same beryllium and aluminum windows were used for the measurement reported in [8]. The measurement results are listed in tables in appendix. It is apparent that the pre-tension in beryllium windows has significantly helped in

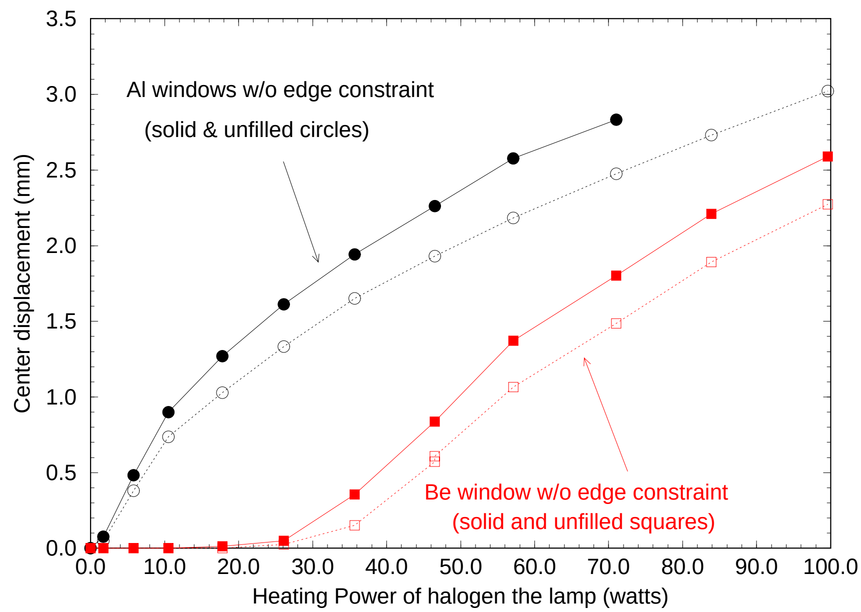

Figure 8: The displacement at the center of the WUT is plotted as a function of the heating power.

keeping the windows from deforming at lower heating powers (lower temperature rise). Once its pre-tension limit is broken at higher powers, the displacement of the beryllium window starts growing linearly with the power with a steep slope. It seems that the displacement is less at the same heating power for the windows without the edge constraints. It turns out this is due to the fact that the temperature rise was driven higher from better thermal conduction between the WUT and the cavity body by the edge constraints as we have discussed above. This is confirmed in Figure 9 where the same measurement results for the beryllium windows were plotted against temperature rise. As exhibited in Figure 9, the displacement for beryllium window with the edge constraint seems to be slightly smaller. It happened to be that the edge constraint helped conducting the heat away from the window and driving the average temperature of the window lower(see Table 3 and 4). The displacement difference may come from the temperature dependent effects from thermal conductivity and thermal expansion coefficient.

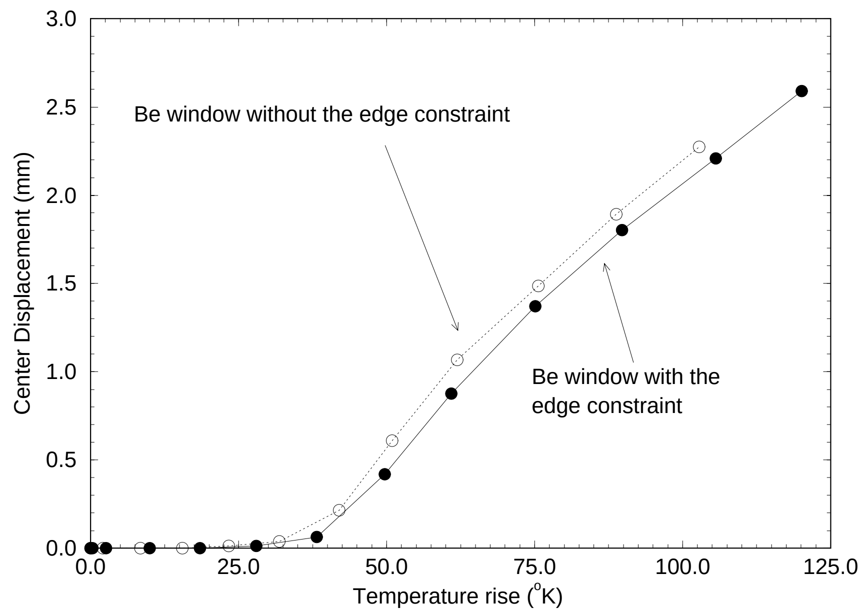

Figure 9: The displacement at the center of the beryllium window is plotted as a function of the temperature rise.

3.3 Frequency Shift

A measurement has been carried out to quantize the frequency shifts as a function of the window displacement. The measurement was conducted utilizing the upper half cell of the cool test model with the beryllium windows. A network analyzer was used to measure the cavity frequency from S_{11} while the halogen lamp was powered. The measurement results are shown in Figure 10. The frequency shift found to be as high as 6.5 MHz at $\Delta T = 120\ ^{o}$K (corresponding to a 2.6 mm displacement at the center of the window). It is worthy to point that the measured frequency shifts from the half cell cavity represent the worst case where both the windows move inwards or outwards together. The measured frequency shifts are consistent with the displacement measurement shown in Figure 9, where the pre-tension did help to keep the window flat at lower powers, which are verified by the frequency measurements.

A MAFIA model was used to simulate the frequency shifts caused by the window displacements. It was concluded that two windows moving in the same direction have much less frequency shifts than the that for the different directions. This suggests that pre-formed windows whose moving directions are predictable may be a possible solution.

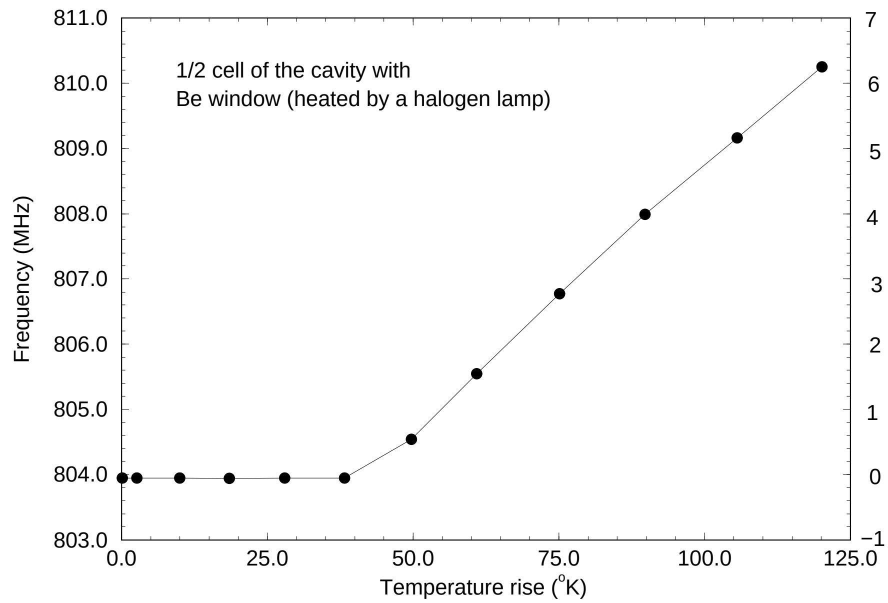

Figure 10: Cavity frequency changes versus the temperature rise in the beryllium window with the edge constraint.

4 Conclusion

The measurements agreed well with the measurements reported in [8]. The window displacements are dominated by the temperature gradient within windows constrained by the annular beryllium frame, not the copper body (expansion) which suggest the way of holding the beryllium windows (frame) to the copper cavity body is not as important as we thought previously. The pre-tension in the beryllium windows does help to reduce the window displacement and keep the window flat below the temperature rise of 30 degrees, but how much and how to put necessary tension to the beryllium windows still needs to be further studied.

References

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A Measurement results on Be and Al windows

Table 1: The pre-stressed Be window with the edge constraint

Power (watts)	T_1 (K^o)	T_2 (K^o)	T_3 (K^o)	T_1-T_3 (K^o)	Displacement (mm)
0.0	22.3	22.2	22.2	0.1	0.000
1.7	24.8	23.5	22.2	2.6	0.000
5.8	32.2	28.5	22.2	10.0	0.000
10.5	41.0	34.2	22.5	18.5	0.000
17.8	51.1	42.2	23.1	28.0	0.0127
26.1	61.8	50.3	23.6	38.2	0.0635
35.7	74.0	60.0	24.3	49.7	0.4191
46.5	85.8	68.7	24.9	60.9	0.8763
57.1	100.9	79.0	25.8	75.1	1.3716
71.0	116.4	90.5	26.6	89.8	1.8034
83.9	133.3	104.5	27.7	105.6	2.2098
99.6	148.8	115.4	28.7	120.1	2.5908

Table 2: The pre-stressed Be window without the edge constraint.

Power (watts)	T_1 (K^o)	T_2 (K^o)	T_3 (K^o)	T_1-T_3 (K^o)	Displacement (mm)
0.0	21.6	21.6	21.6	0.0	0.000
1.7	23.9	22.6	21.8	2.1	0.000
5.8	31.2	27.9	22.8	8.4	0.000
10.5	39.8	34.5	24.3	15.5	0.000
17.8	49.6	42.2	26.3	23.3	0.0127
26.1	60.6	52.1	28.7	31.9	0.0381
35.7	74.1	63.3	32.1	42.0	0.2159
46.5	86.1	73.6	35.2	50.9	0.6096
57.1	100.5	85.1	38.6	61.9	1.0668
71.0	117.1	97.0	41.5	75.6	1.4859
83.9	133.8	110.4	45.0	88.8	1.8923
99.6	151.7	124.9	48.9	102.8	2.2733

Table 3: The non-stressed aluminum window with the edge constraint

Power (watts)	T_1 (K^o)	T_2 (K^o)	T_3 (K^o)	T_1-T_3 (K^o)	Displacement (mm)
0.0	24.4	24.3	24.3	0.1	0.000
1.7	25.6	25.2	24.7	0.9	0.0762
5.8	31.4	28.3	24.9	6.5	0.4826
10.5	39.2	33.7	25.3	13.9	0.9017
17.8	47.8	39.7	25.6	22.2	1.2700
26.1	57.3	45.6	25.9	31.4	1.6129
35.7	67.8	53.6	26.3	41.5	1.9431
46.5	79.1	61.5	26.8	52.3	2.2606
57.1	92.7	69.2	27.5	65.2	2.5781
71.0	106.7	79.2	28.3	78.4	2.8321

Table 4: The non-stressed aluminum window without the edge constraint

Power (watts)	T_1 (K^o)	T_2 (K^o)	T_3 (K^o)	T_1-T_3 (K^o)	Displacement (mm)
0.0	23.5	23.3	23.1	0.4	0.000
1.7	25.1	24.6	23.2	1.9	0.0508
5.8	30.4	27.6	23.7	6.7	0.3810
10.5	38.5	33.1	25.2	13.3	0.7366
17.8	47.3	39.5	27.1	20.2	1.0287
26.1	56.5	46.8	29.5	27.0	1.3335
35.7	69.0	54.2	32.0	37.0	1.6510
46.5	80.2	63.3	34.8	45.4	1.9304
57.1	91.6	73.0	37.9	53.7	2.1844
71.0	104.8	81.5	41.3	63.5	2.4765
83.9	117.8	92.1	44.2	73.6	2.7305
99.6	132.7	101.7	47.7	85	3.0226