Vibration Reduction in X-ray Capillary Optic Fabrication

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Glass capillary optics are used to focus X-rays from synchrotron light sources. The quality of Cornell High Energy Synchrotron Source (CHESS) capillaries matches present generation light sources well, but improvements will be necessary to take advantage of planned facilities, such as the Energy Recovery Linac (ERL). The primary obstacles are small radius profile errors and centerline oscillations in capillaries drawn from constant-diameter glass tubing into an elliptical shape. This project focuses on minimizing mechanical vibrations in the capillary fabrication and analysis system. Capillary errors are compared before and after structural bracing additions; these additions were found to reduce errors and enable the drawing of some of the best capillary optics to date.

I. INTRODUCTION

X-ray beams are very difficult to focus. They only reflect at very shallow angles. The critical angle is given by $\theta_c = 32$ keV / E_c * milliradians, where E_c is the energy of incident X-rays. One mrad is 0.06° , so a 32 keV X-ray will only reflect when incident at 0.06° or less. This difficulty led to the invention of elliptically shaped glass capillary optics that function at glancing angles of incidence. Capillary optics work by placing the X-ray source at one focus of an ellipse and the sample to be studied with X-rays at the other focus (Figure 1). These optics focus X-rays of any energy under their designed critical energy, in two dimensions. They are also fairly compact (5-20cm long; <1mm wide) and robust to X-ray damage. [1]

Capillary optic quality, at the scale needed for the ERL, is hampered by μm sized radius profile and centerline errors. These are differences between the designed and measured radius profile and centerline. Another important way to quantify error is through slope errors. Since the important factor in capillary operation is the angle at which incident X-rays strike the surface, slope errors provide a great way to quantify differences from the ideal. Slope errors for CHESS capillaries are on 10s of μrad scale.

These errors are caused by oscillations in the radius profile (Figure 2) and centerline. The goal of the CHESS capillary group is to minimize these oscillations. This study attempts to do so by reducing mechanical vibrations in the capillary fabrications process.

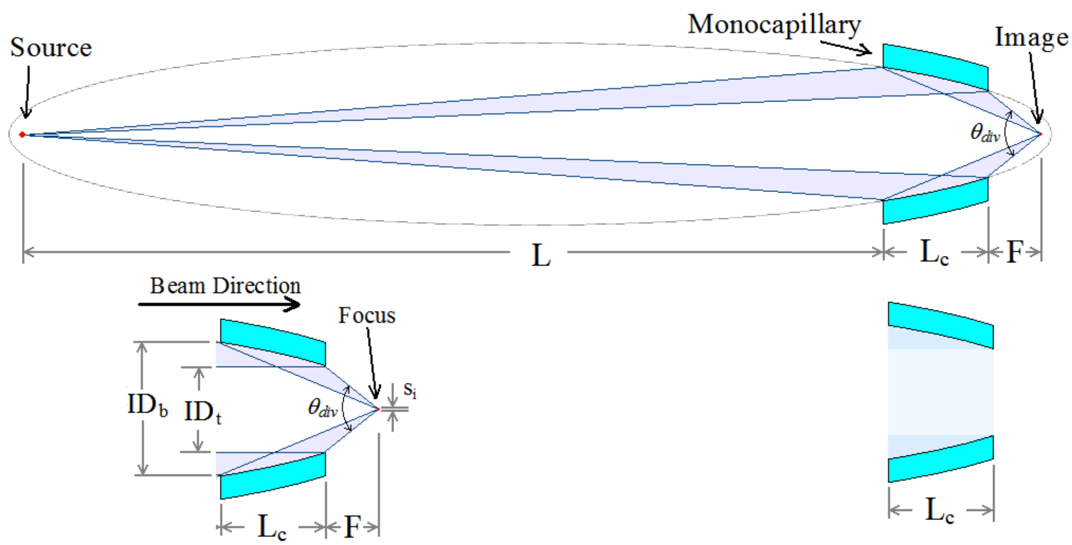


Fig. 1: (Top) Elliptical capillary optics use the principle that a ray from one focus will be reflected to the other focus by a single bounce. In this case the source of X-rays is at one focus and the sample to be studied with X-rays will be at the other ("Image") focus. The capillary base to source distance, L = ~30m, capillary length, L_c = 5-10cm, capillary tip to focus, F = 10-100mm, and capillary divergence, θ_{dv} = 2-10 mrad. (Bottom Left) The base inner diameter, ID_b = 0.5-1mm, the tip inner diameter, ID_t = 0.1-0.5mm, and the spot size, s_i = 0.25-100 μm.

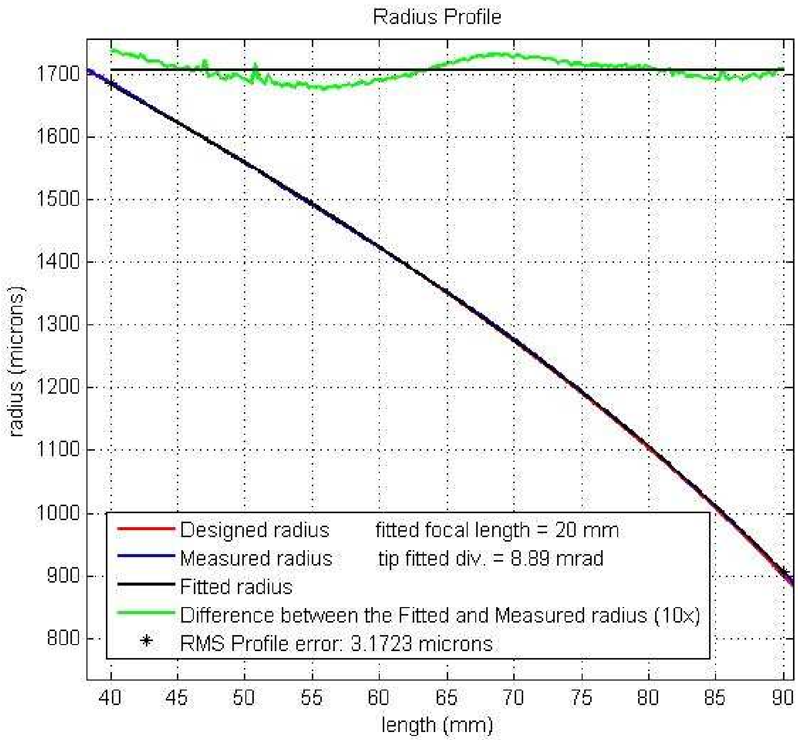


Fig. 2: This is the profile of an average capillary pulled before this project began. The red line is the designed radius profile along the capillary, the blue line is the measured radius along the capillary, and the black line is an ellipse fitted to the blue measured radius. The green line is the difference between the black fitted radius and the blue measured radius magnified 10x. The differences are very small, as the RMS profile error shows.

II. Capillary Fabrication

The CHESS capillary optic fabrication process begins with borosilicate glass capillary tubes purchased from suppliers. Quality is very important; original radius or centerline profile errors may be decreased by the pulling process, but remain after fabrication. The glass capillary tube is then mounted in the capillary puller (Figure 3).

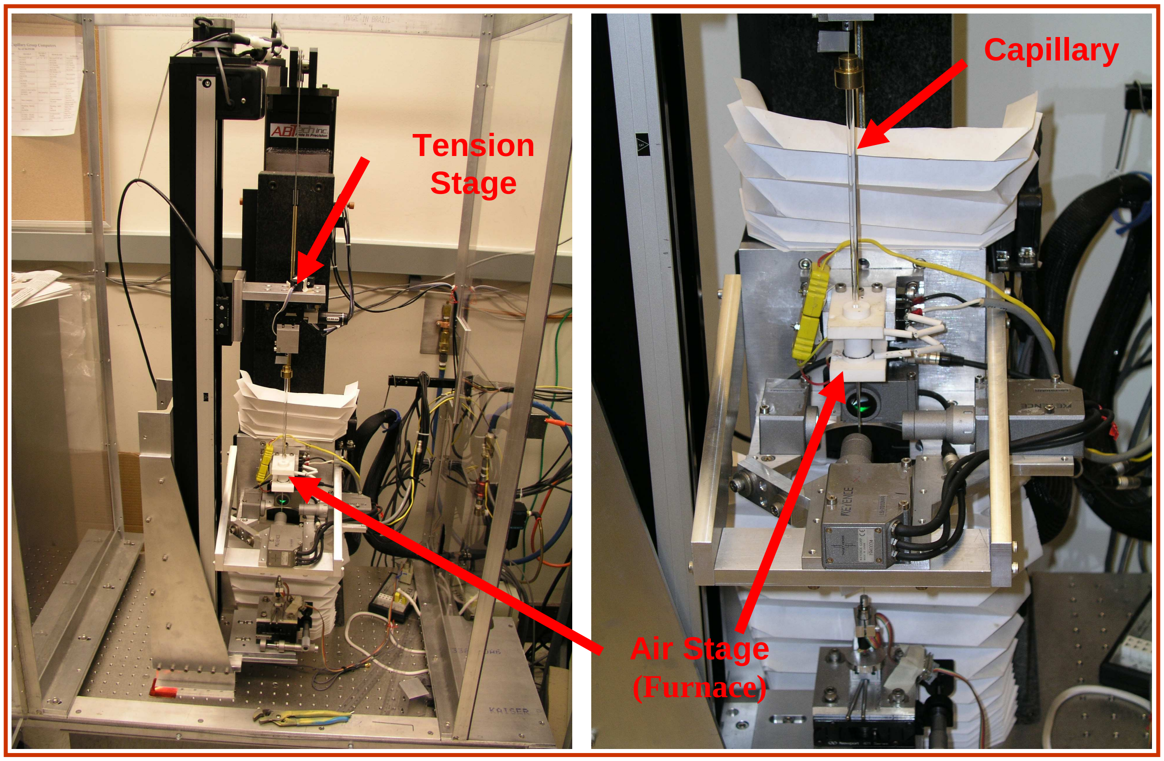


Fig. 3: (Left) Capillary puller. The glass capillary is held in tension from above by the tension stage. This stage moves along the black pillar on the left to adjust the tension. (Right) Close up of air stage, furnace, and capillary. The air stage is mounted on the rear pillar and is also moveable. It holds the furnace. As the glass is heated, the tension stage pulls it upward reducing its radius. With the moving stages, the radius can be shaped into the desirable elliptical profile.

The capillary is attached by strings to a movable tension stage. The stage is moved to control the tension on the capillary. A separate air-bearing stage is used to control the position of a furnace. As the glass is heated at 600°C - 700°C the tension causes the capillary to stretch and become thinner. By adjusting the amount of tension and the position of the furnace, the capillary can be shaped into the desired elliptical radius profile. The tension stage and air stage are controlled by a LabVIEW program to precisely adjust the capillary tension and furnace position.

After the fabrication process, before the capillary is removed from the puller, the capillary is scanned by Keyence optical micrometers mounted on the air stage. These micrometers measure the width and position of the shadow cast by the capillary in a laser beam. These measurements are used to analyze the radius and centerline profiles of the capillary. Capillaries presently in use have profile errors from 0.5-2 μm rms and slope errors from 20-80 μrad rms.

Whenever the synchrotron is running, which did not happen during this REU program, capillaries are also tested in the X-ray beam. A "Far Field Image" is taken from a distance beyond the focal point of the capillary (Figure 4) [1]. This provides insight into the quality of the capillary. Oftentimes, structure is revealed in the far field image, which reflects errors within the capillary.

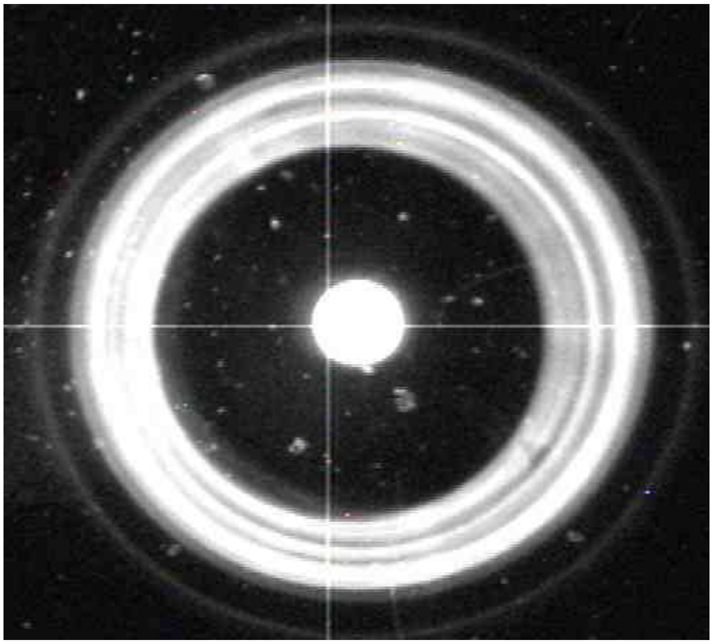


Fig. 4: Far Field X-ray Image: X-ray image taken from beyond capillary focal point. Center spot is the x-ray beam that goes straight through the center of the capillary without reflecting. It will be blocked during actual capillary use. The ring is made of X-rays reflected off of the capillary. The structure within the ring is caused by imperfections in the capillary's interior profile.

III. Vibration Reduction

This project attempts to reduce oscillations in capillary profile by studying and reducing mechanically-induced vibrations in the fabrication and measurement system. To reduce vibrations, structural bracing is added to the capillary puller system. An aluminum cross bar and steel green bar are added to the puller as can be seen in figure 5. The cross bar connects the tops of the air stage and tension stage supports and is oriented primarily in the y direction (see axis definition in figure 5). It is intended to provide more rigidity due to connecting the two beams. The green bar is connected to the top of the tension stage support to provide it stability along the x-axis. The tension stage support is thinner along this direction, justifying extra bracing. It is important to note that the green bar is attached directly to the floor, while the rest of the puller system is isolated on a granite table. This may have some effect on results.

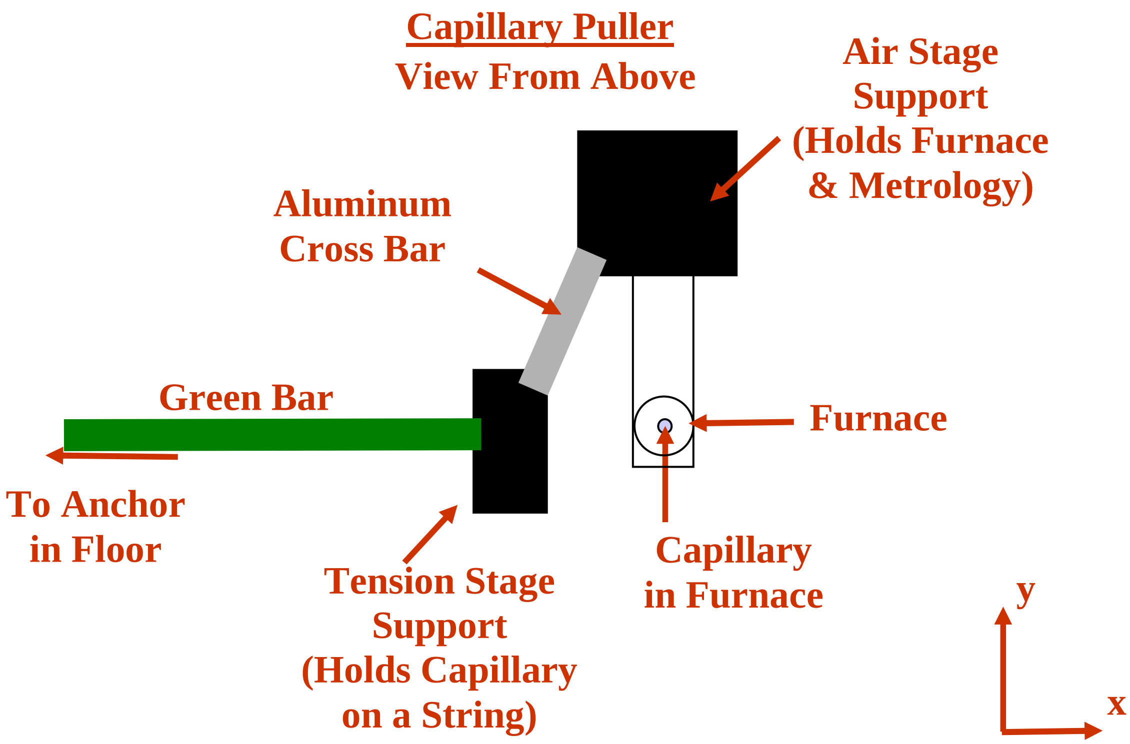


Fig. 5: The capillary puller consists of an air stage and a tension stage. The air stage controls the position of the furnace and optical metrology. The tension stage holds the top of the capillary with a string. It controls the tension on the capillary. During this project an aluminum cross bar was added between the tops of the stage supports to make the system more rigid. A green steel bar was also added that anchors the top of the tension stage to the floor. These supports should stiffen the system and decrease vibrations.

The different supports where evaluated by a series of “ping tests” in which a standard “knock” was applied to each support along both axes. The ping was applied with the standard “knock” system shown in figure 6. These tests where applied with each configuration of structural bracing: no bars, cross bar only, green bar only, and green and cross bar. Displacement was measured on a capillary that was mounted and placed in tension.

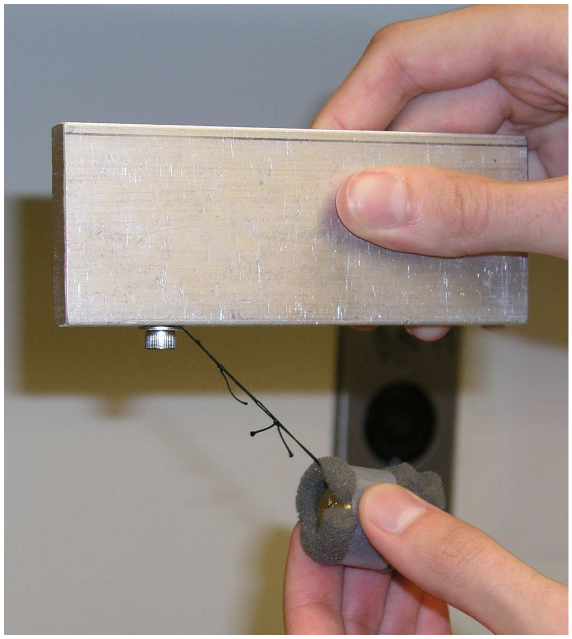
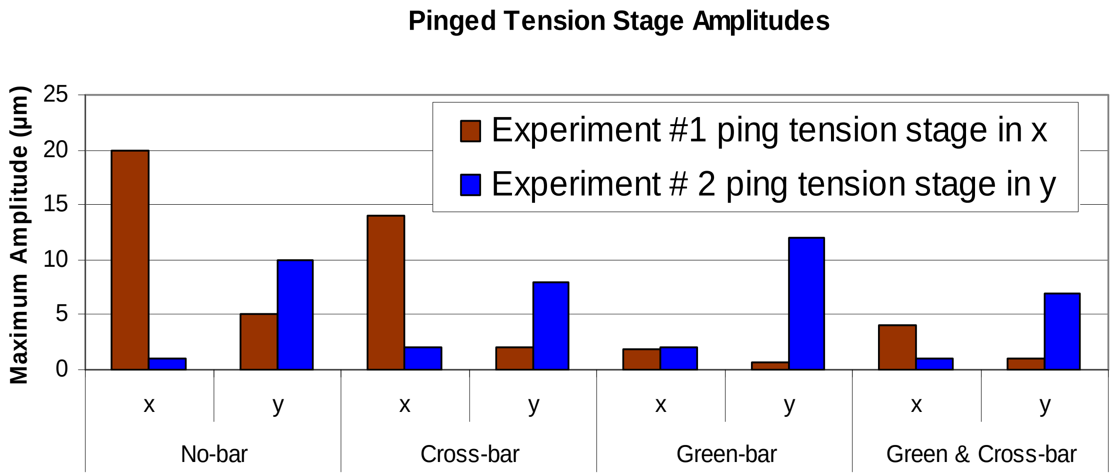


Fig. 6: The standard "ping" system is a 100g weight wrapped in foam padding hanging off of a 5cm string. The weight is brought back to the horizontal and released to "ping" its target. This is repeated on both stage supports of the puller along both the x and y axes. The amplitudes are then measured and compared.

Maximum oscillation amplitude was then compared under different bracing conditions (see figure 7). Logically, the combination of both bars had the smallest amplitude overall. The green bar also greatly reduced amplitude along the x-axis it is positioned along. It does increase the amplitude along the y-axis transverse to the bar's orientation. This may be due to the thin cross-section of the green bar in the y direction. Interestingly, the cross-bar doesn't have a large effect on the y-axis vibrations; it actually has more of an effect over the x-axis. That may be due to the weakness of the tension stage beam in the x-direction. Any support may improve it. This experiment justifies increased support in both the x and y directions to reduce vibrations.



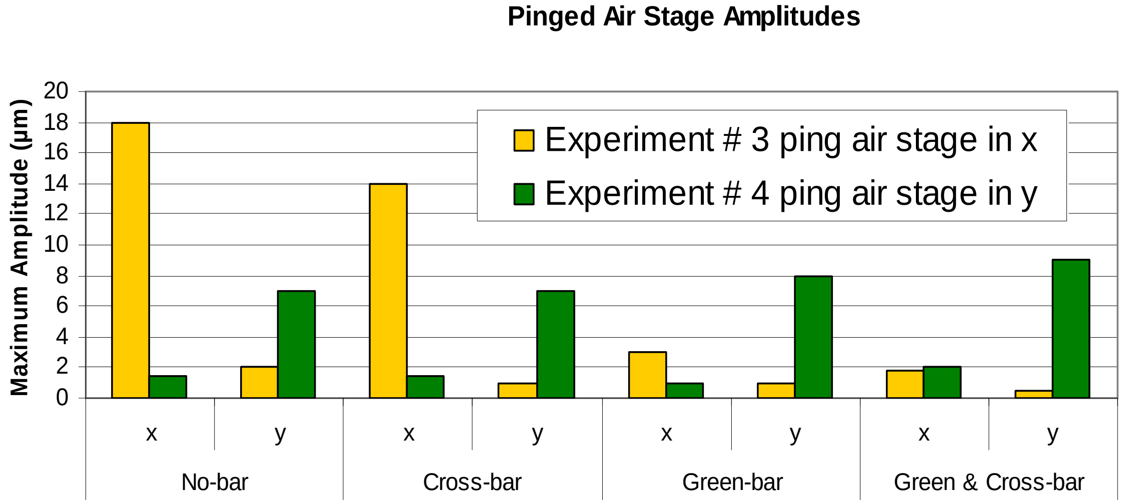


Fig. 7: These graphs show four "ping test" experiments that measure the maximum amplitude of measured vibrations. Each experiment was pinged at a different point, either the air or tension stage in the x or y direction. These ping tests where performed with each different configuration of reinforcing bars: no bar, cross bar only, green bar only, and both the green and cross bar. This allows the vibration reduction of each reinforcement to be measured. The x and y along the bottom of each graph represents vibration *measurement* along the x and y axes. As expected, the green bar, which runs along the x-axis, reduces x-axis vibrations, and the cross bar reduces y-axis vibrations. Interestingly, the green bar adds amplitude along the y-axis vibrations. This may be due to the green bars thin cross-section along that axis.

Another part of this project is to try to find sources of vibrations that may cause capillary oscillations. To try to find the fundamental frequency of the tension and air stage supports, they are approximated as solid cantilever beams. Much information is available about cantilever beams, because of their use in MEMS devices, such as oscillators and accelerometers. The fundamental frequency formula for a cantilever beam fixed at one end is:

$$f_n = \frac{\kappa_n^{\ 2}}{2\pi}\sqrt{\frac{EI}{\rho A L^4}} \tag{1}$$

Where κ_n is a constant for each oscillation mode; for mode 1, it is ~1.875. E is the Young's Modulus of the beam, I is the area moment of inertia, ρ is the density, A is the cross-sectional area, and L is the length. For a solid beam with one end fixed:

$$I = \frac{bd^3}{12} \tag{2}$$

Where b is breadth and d is depth. Depth is along the axis of vibration. Once the relevant numbers were substituted into the formula, $f_{air\ stage}$ = 100 Hz and $f_{tension\ stage}$ = 45 Hz. These numbers are much too high. The oscillations in the capillaries occur at around 1 Hz. The measuring system can only measure up to 5 Hz, so this is far from our range of measurement. This is probably due to the moment of inertia, in reality, being much lower. The formula is for a solid beam, while neither beam is actually solid. The air stage support is hollow, and the tension stage support is made of a more complex combination of bars. Their moments of inertia should be much lower, causing their resonant frequencies to be lower. These equations are still useful, because they show how the fundamental frequency is related to the physical characteristics of a cantilever.

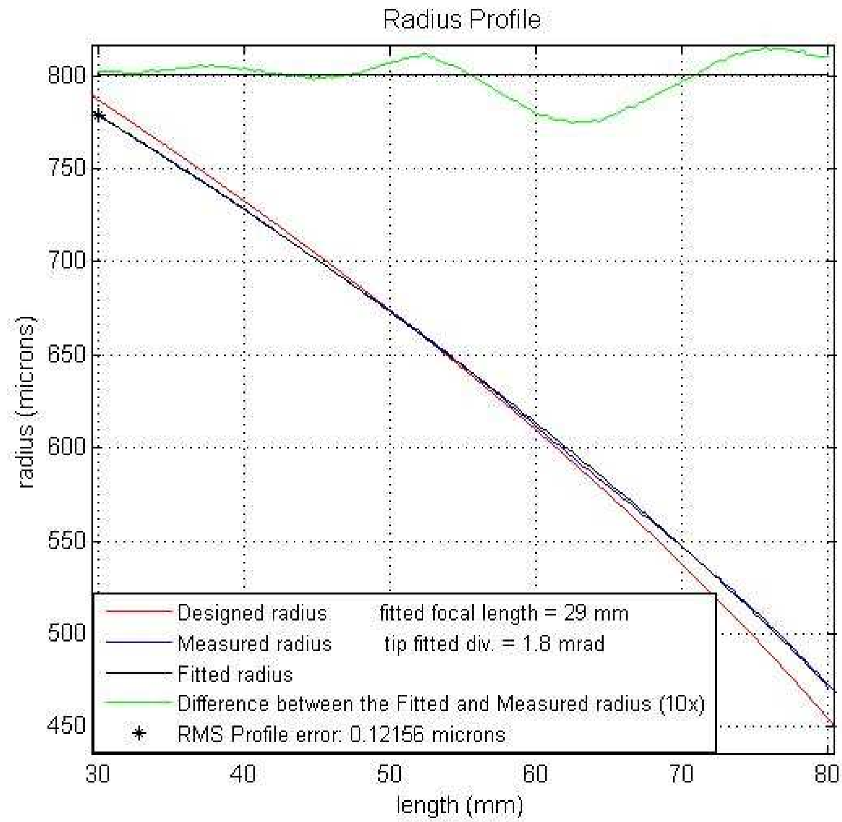


Fig. 8: This plot shows the radius profile of a capillary pulled after this project's structural improvements where put in place. The RMS profile error, 0.12 μm, is much smaller than in the before improvement plot in figure 2, 3.17 μm.

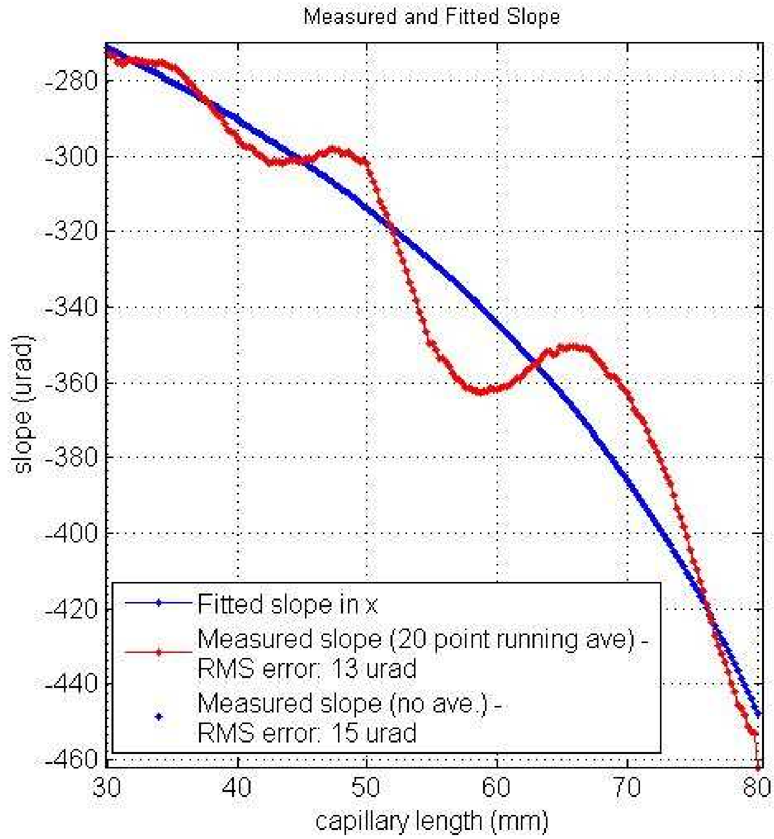


Fig. 9: This is the profile slope graph matching fig. 8. Even though the oscillations look large, the y-scale is very small, and this RMS slope error is on of the smallest measured.

IV. Conclusions

The primary goal of the capillary group is to make better capillaries. This project shows that improving structural bracing on the capillary puller helps to mitigate vibrations and oscillations in the capillaries. Figure 8 shows the radius profile and figure 9 shows the slope profile of a capillary pulled after the structural improvements where installed. The radius profile and slope errors are at new lows, significantly smaller than in the capillary before this project in figure 2.

Soon the green bar will be replaced with a more permanent solution, shown in figure 10. Triangular bracing and a larger base should reduce tension stage vibrations, especially in the x direction. The new bracing should also not enhance y-axis vibrations like the green bar has.

The question about the source of vibrations is left unanswered. Maybe the capillary mounting system needs to be studied further. Capillaries are held in tension by strings. The capillary's motion seems to be controlled by those strings, so maybe that is a system that needs to be analyzed in detail.

Finally, the glass pulling improvement has put the metrology is at its limits. Profile errors are often under 1 μm rms, and have been measured to less than 100 nm rms. This is far bellow the accuracy of the Keyence metrology system, which is 0.5 μm. Hopefully a more accurate system can be found to scan the capillaries. Other possibilities are available, such as cutting open capillaries to analyze there internal profile. A more accurate simple replacement for the present system would be nice, though.

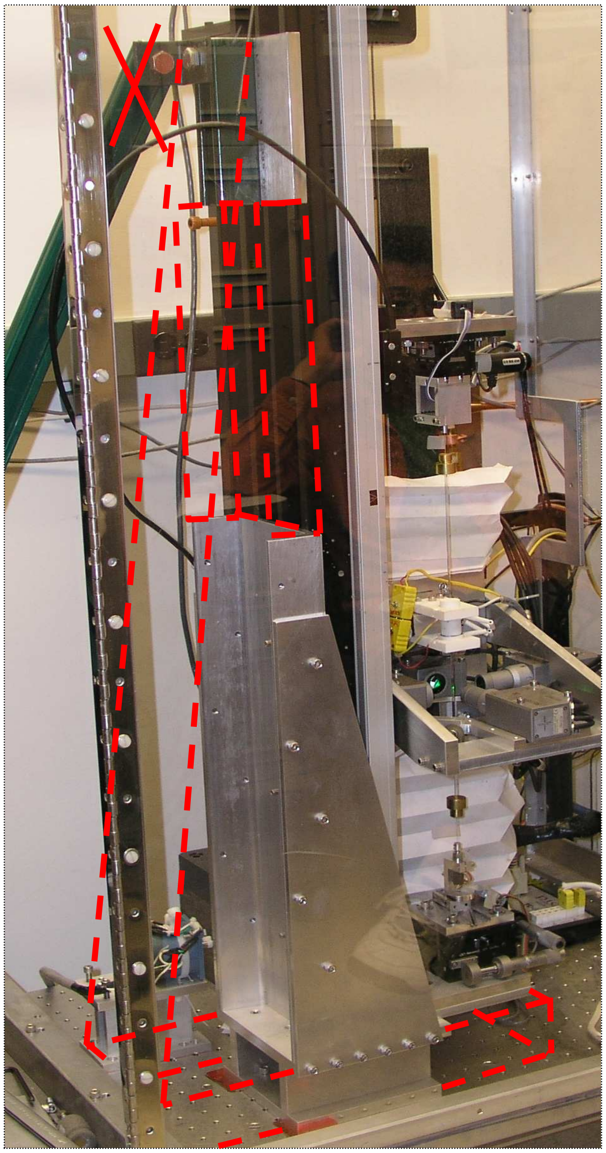


Fig. 10: Future improvements to the capillary puller include a triangular support to replace the green bar. This triangular support would reach from the bottom left of the picture up to the top of the tension stage. The aluminum beam attached to the left of the tension stage will also be extended. A larger, more stable base for the tension stage is also planned.

VI. ACKNOWLEDGEMENTS

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[1] S. Cornaby. The Handbook of X-ray Single-Bounce Monocapillary Optics, Including Optical Design and Synchrotron Applications. Cornell University Dissertation (2008).