Vibration Studies at CHESS

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Dated: 7 August 2009

Mechanical stability is an important factor in the performance of many systems at the Cornell High Energy Synchrotron Source (CHESS), so it is ideal to minimize vibration wherever possible. The F3 monochromator crystals, the Monstab unit currently in use in the F3 line, the Capillary Puller, and the synchrotron light experiments at L3, 23 West, and 23 East in the tunnel were among the systems studied. Vibration was measured using Wilcoxon seismic accelerometers [1], and then the raw data was analyzed using specialized computer software using the Fast Fourier Transform (FFT). This paper presents an analysis of the vibration in a variety of systems at CHESS.

I. INTRODUCTION

Vibration is everywhere. It could be caused by traffic on the nearby streets, pressurized water flow, or even electrical oscillation. The difficult part is trying to locate the source of vibration in a way that will allow us to damp and/or prevent it.

Many systems at CHESS require a high degree of stability, and even the tiniest vibration can affect their performance. Only a handful of systems were studied during the course of this project. Monochromator crystals select a narrow band of wavelengths from a “white” x-ray beam by adjusting their angle relative to the beam. Cooling water that flows through coils of copper tubing around these crystals can cause them to vibrate. Another source of vibration for the monochromator crystals is the Monstab system, which continuously adjusts their angle relative to the beam. The capillary puller is used to create precise x-ray focusing optics from thin glass tubes. The motors that move its different parts contribute significantly to the overall vibration of the system. The synchrotron light experiments around the Cornell Electron Storage Ring (CESR) collect optical radiation from the beam and reflect it down into an optical bench, using a series of mirrors. This set-up is sensitive to vibrations from the water used to cool the mirrors.

These are some obvious sources of vibration, but it is by no means a complete list. In the end, the best possible outcome is to identify a few sources of vibration, and try to damp them.

II. METHODS

Throughout the course of this project, vibration data was taken with Wilcoxon accelerometers (models 731A and 731-207) [1]. Piezoelectric accelerometers convert a physical force (the motion of a mass on a piezoelectric cantilever inside the accelerometer) into an electrical signal, which is proportional to the force measured. This signal was amplified, sent to an analog-to-digital converter, and finally read by specialized computer software USB DAQ FFT [2]. Data was taken at a sample rate of 2500 Hz, with 8192 samples. The data were then analyzed, using the Fast Fourier Transform (FFT), to give the amplitude of the vibrations [3]. To correct for small aberrations (i.e. someone walking by, or the use of loud machinery), plots were averaged in sets of 10 or 50. The FFT converts a signal in the time domain to a signal in the frequency domain. In this manner, one can see very clearly the frequencies where each system was vibrating. One unfortunate drawback of this process is that, for very low frequencies, the math involved in computing the FFT causes a spike in amplitude as A→ zero. This is called 1/*f* noise [3].

$$A(f) = \left(\frac{-1}{\omega^2}\right) g(f) \qquad (1)$$

Where A is the amplitude, g is the acceleration, both A and g are functions of frequency *f*, and $\omega = 2\pi f$.

Fig. 1: 731A ultra low frequency seismic accelerometer (left) and 731-207 low frequency seismic accelerometer (right)

A circuit was designed to add or subtract the signals from two accelerometers. In this manner, it was possible to affix both accelerometers to an object, and then determine if the object was vibrating all in the same direction (translation motion) or in opposing directions (rotational motion). Then, looking at a plot of amplitude vs. frequency, if the A+B line is higher, the object is vibrating translationally. If the A-B line is on top, the object is vibrating rotationally.

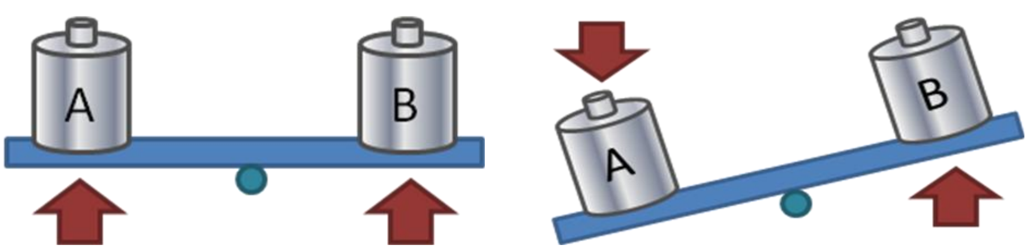


Fig. 2: Translational Motion (left) and Rotational Motion (right)

III. A SIMPLE MODEL

To study the vibrations caused by the flow of cooling water, a simple model was created in an approximation of the cooling coils that surround the first (upstream) monochromator crystal in the F3 line. This coil, made from ¾ inch copper wire, was 5” in diameter, with 11 loops. It was connected to the CHESS water system, and Wilcoxon 731-207 and 731A accelerometers were used to measure the vibrations on each loop. While this set-up was not a perfect analogy to the real cooling coils, it provided an easy way to observe the effects of the CHESS cooling water on an isolated system. The cooling water is kept in a large tank, at 30°C, and it is pumped through the system at about 1 gallon per minute.

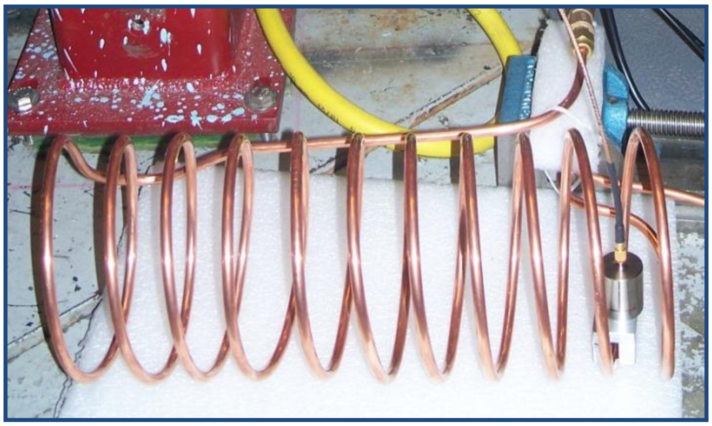


Fig. 3: A simple model used to study the vibration caused by the cooling water

Preliminary results from the model coil system showed a large amount of vibration in the low frequency (5-20 Hz) range. This happens to be the range where it would be most advantageous to prevent vibration. Some improvement was shown when both ends of the coil were tightly constrained. The flow rate doesn’t affect the amplitude of vibration in the coils. Even at 1/5 normal flow rate, the vibration is not noticeably damped.

In an effort to reduce vibration, a “vibration filter” was made from a water filter canister, filled with small marble chips. This filter forced the water to move around the small rocks, preventing any uniform movement, and thus damping the vibrations.

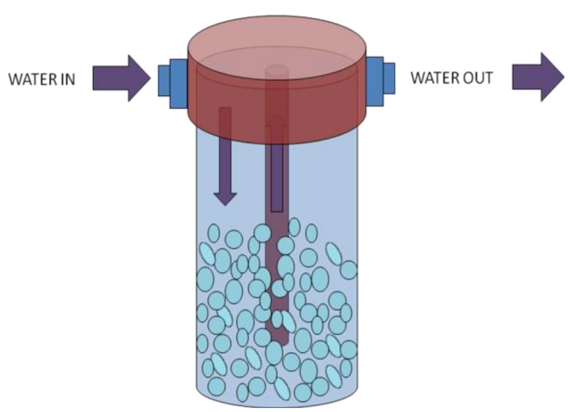


Fig. 4: The “Vibration Filter”

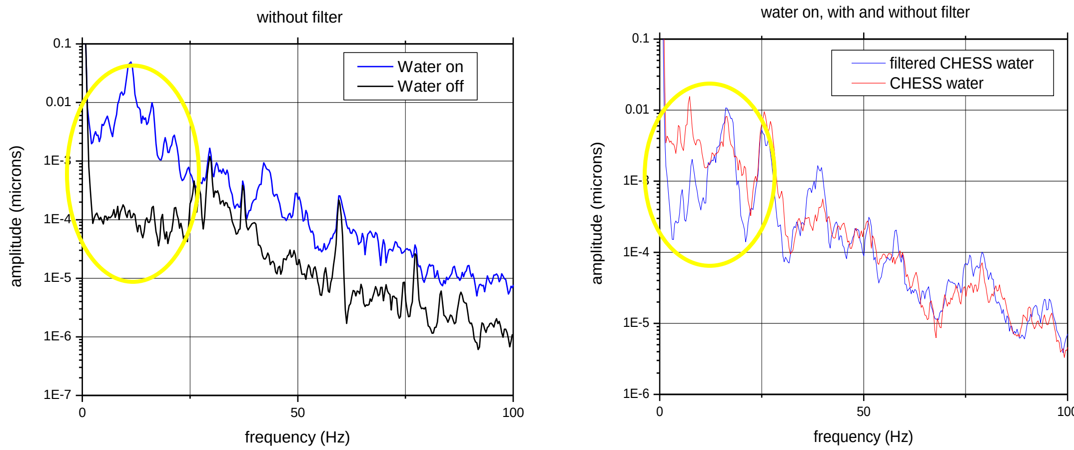


Fig. 5: The addition of a water filter into the CHESS water line results in a significant drop in vibration at low frequencies

IV. THE F3 MONOCHROMATOR CRYSTALS

The monochromator crystals that focus the x-ray beam going to F3 sustain a considerable amount of heat. Chilled, pressurized water from the CHESS water supply flows through copper coils around the first monochromator crystal, to help dissipate this heat. The water flow causes vibration that could affect the performance of the crystal and ruin the focus of the beam. A special stage was prepared to hold the two 731-207 seismic accelerometers in place, first in the position of the Mon U crystal, and then in the position of the Mon D crystal. The accelerometers could be positioned perpendicular to the beam (as shown in Figure 6), or parallel to the beam.

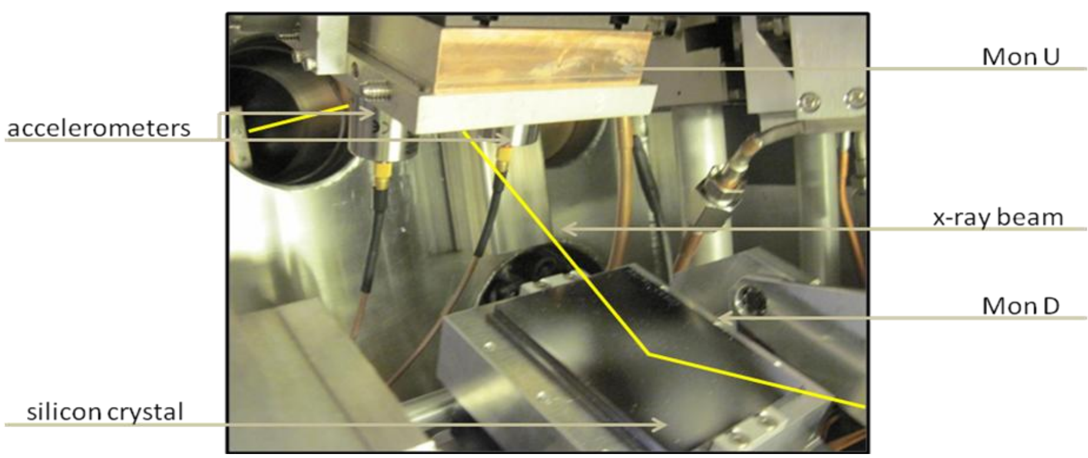


Fig. 6: The accelerometers are mounted on the Mon U stage

Mon U vibrated at very low frequencies (5-20Hz) when the cooling water was turned on, but unlike the simpler model coil, it also vibrated in the slightly higher 20-100Hz range. By contrast, Mon D showed significant additional vibration *only* above 20Hz when the water was turned on.

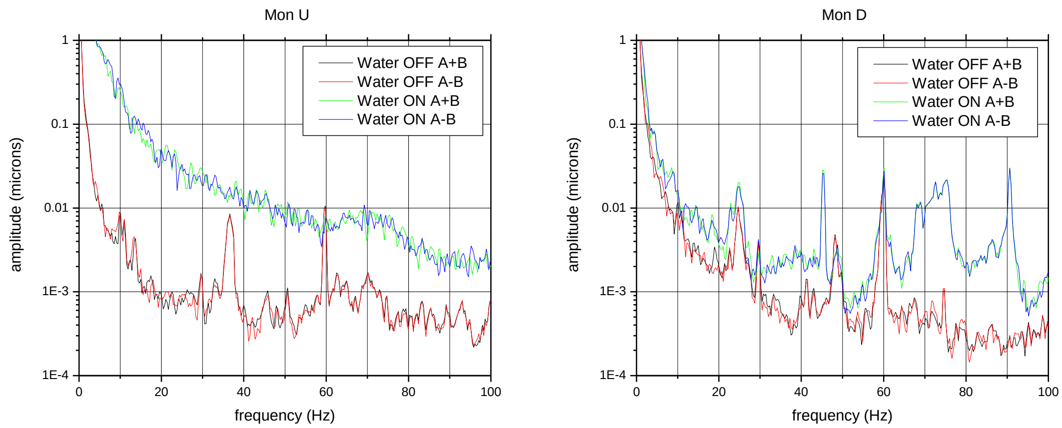


Fig. 7: Mon U and Mon D with cooling water ON and OFF

The cooling water runs though coils that are next to Mon U. Therefore, it is unsurprising that Mon U vibrates at higher amplitude than Mon D when the water is turned on. For both crystals, the A+B and A-B data lines cross each other often. The monochromator crystals experience translational as well as rotational vibrations.

The cooling water certainly affects Mon U the most—and this is bad news. In order to study the response of the two monochromators to a single stimulus, a speaker (with a function generator) was used to drive the entire F3 coffin at its resonant frequencies.

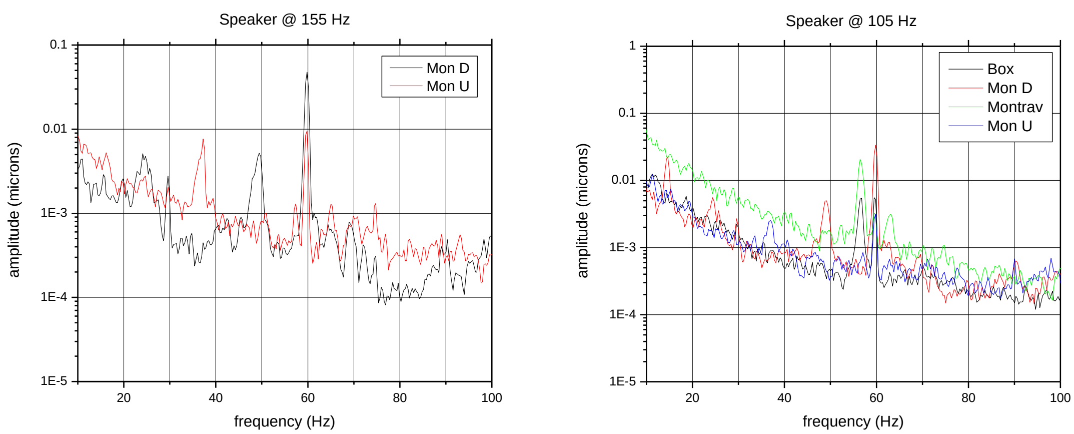
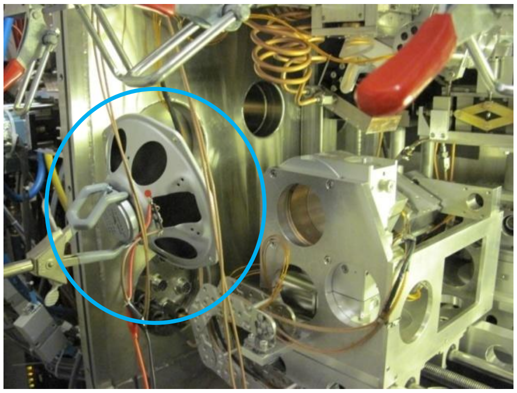


Fig. 8: Speaker-driven vibrations in the F3 coffin

Here, since Mon U vibrates at greater amplitude, we can say that it is less stable than Mon D, since each element was affected by the same sound waves. 105Hz was the most obvious resonant frequency of the box—it was almost painful to listen to stand right next to it. At this frequency, the Montrav vibrates with the greatest amplitude, while the box and the monochromators were roughly the same. Any noise at the resonant frequencies of the box could cause everything inside to vibrate—it is important to take these resonant frequencies into account during the design phase.



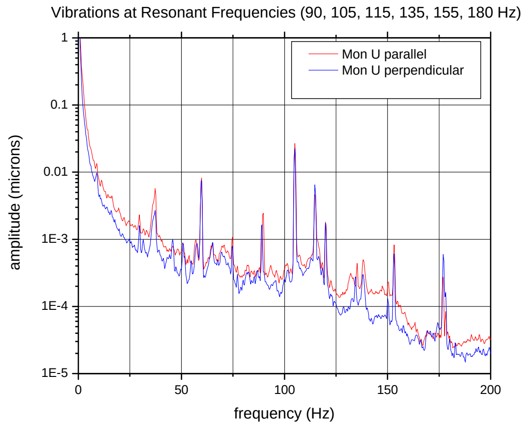


Fig. 9: Mon U vibrates more in the direction of the beam line (accelerometers parallel to the beam) than in the transverse direction (accelerometers perpendicular to the beam).

When there is an x-ray beam present, the Monstab system is used to stabilize the angle of the monochromator crystals, using a feedback scheme. Therefore, it would be great to devise a method for measuring the vibration of the monochromator crystals with and without the Monstab units—but, for the time being, they were studied separately.

V. THE MONSTAB SYSTEM

The vibration caused by the movement of the Monstab system was analyzed next. The Monstab system is used to make minute adjustments to the angle of the monochromator crystal. The Monstab unit tells a piezoelectric actuator where to move, to re-align the monochromator with respect to the beam. For the purposes of this project, a simpler model (see Figure 10) was used to approximate the actual set-up, to test the stability of two different Monstab units. The old, analog Monstab unit moves the piezoelectric actuator in a uniform motion. The new unit is digital, and moves the actuator in a stepping motion. In the model set-up, a laser beam was reflected from a mirror one meter away, then back into a photodiode. The beam was interrupted by rolling a small metal cylinder through its path, just in front of the photodiode. Two 731-207 seismic accelerometers were mounted next to the piezoelectric actuator, to record the vibration that was caused as the system adjusted to try to regain its original position.

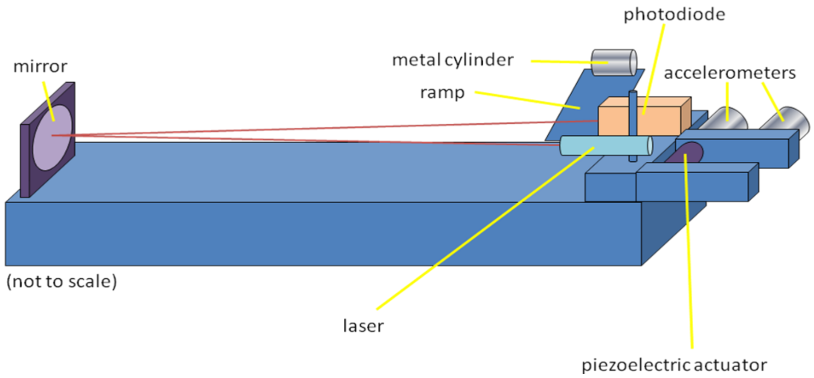


Fig. 10: The experimental set-up for testing the Monstab units

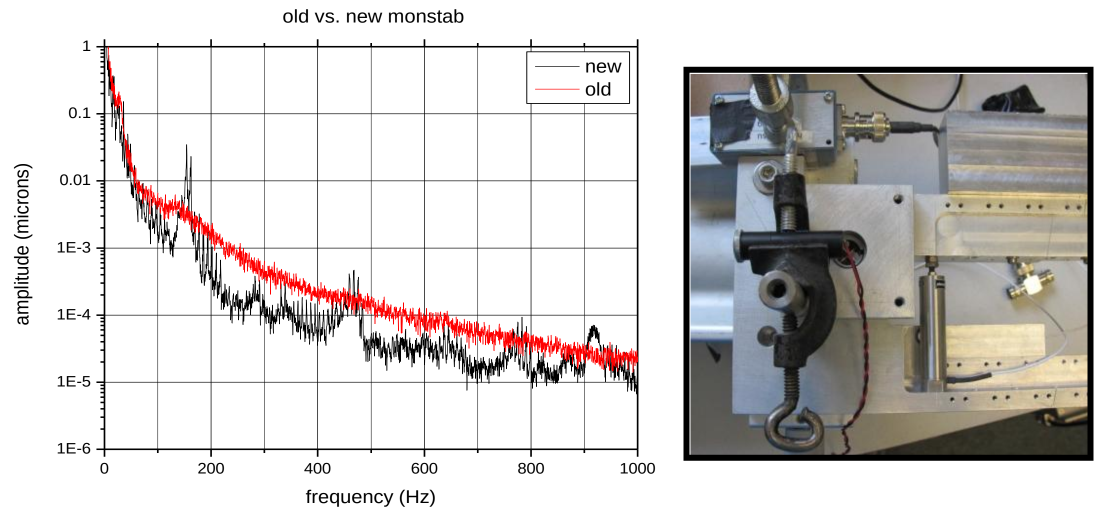


Fig. 11: A comparison of the vibrations caused by the old and new Monstab units

This plot shows the vibration caused by the two different Monstab units while they were searching for the correct beam position. The new Monstab unit moves in a stepping motion, which results in a choppy plot, while the old one moves more smoothly (but vibrates more overall).

VI. THE CAPILLARY PULLER

The capillary puller is a very sensitive instrument that heats glass tubes to extremely high temperatures (600-700°C), as it pulls and rotates the heat-softened tubes to form precise, elliptically-shaped capillaries [4]. These capillaries focus x-ray beams for experimental use. Vibration during the cooling phase could cause the capillaries to harden into imperfect shapes.

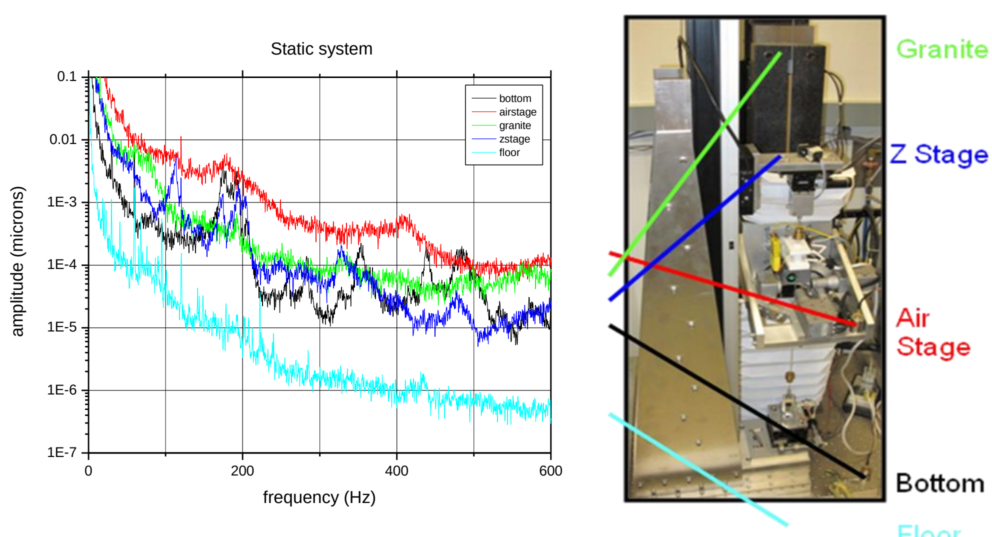


Fig. 12: The capillary puller, at rest

The top of the glass tube is connected to the Z stage, which performs the actual pulling. The air stage is connected to a tall slab of granite through an air bearing system. The air stage holds the furnace, which heats the glass tube, and several micrometers, which allow close observation of the tube during the pulling process. The granite block, the Z stage, and the bottom of the puller vibrate in the same manner, since they are rigidly connected. The air stage vibrates more than the other elements in this system, since it is not rigidly connected to anything. The floor vibrates the least.

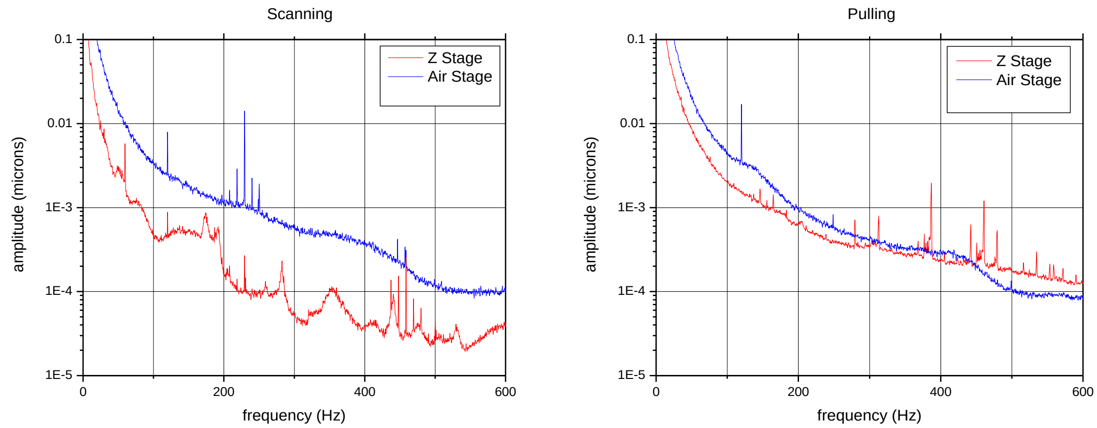


Fig. 13: The capillary puller performs two distinct motions. It scans the glass tube for imperfections, and then heats and pulls the tube into an elliptical shape.

When the capillary puller is scanning the glass tube, the air stage moves and the Z stage is still. This stage is diagnostic, and the glass tube is not changed. The air stage vibrates much more than the Z stage during this process. When the capillary is being pulled, a stepping motor moves the Z stage upward, while the furnace (on the air stage) heats the glass tube. The motor causes the Z stage to vibrate. During this process, the two stages vibrate at roughly the same amplitude.

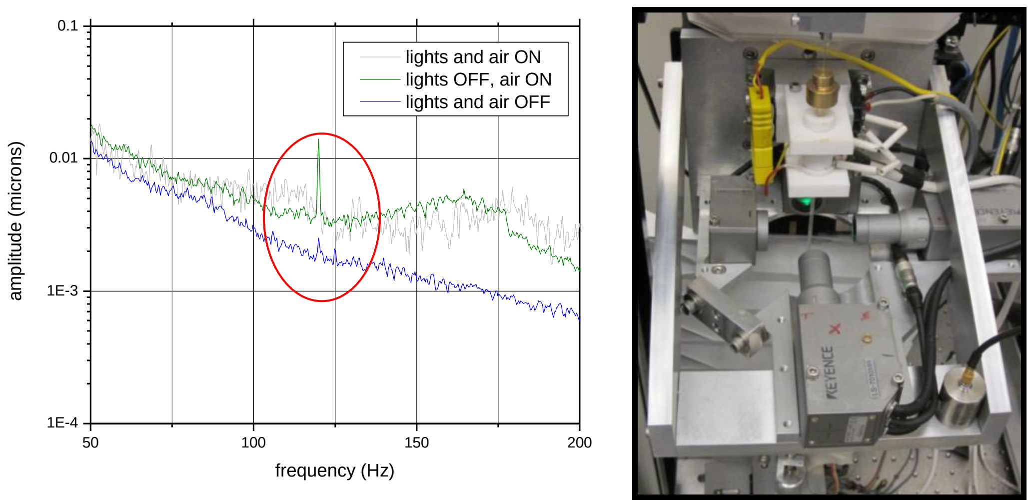


Fig. 14: Air stage, all systems at rest

Previous measurements (using the optical micrometers mounted on the air stage) suggested that the spike in vibration amplitude at 120Hz was due to the fluorescent lights above the capillary puller. The gray line in Figure 14 shows the vibration of the air stage when the puller is at rest, with the lights on, and the green line shows the vibration with the lights off. The lights do not cause the 120Hz vibration, and previous measurements were probably affected by ambient light, rather than mechanical vibration. The blue line shows the vibration when the lights AND the air bearing are turned off. In this case, the 120Hz spike is much smaller. It is reasonable to conclude that this spike was caused by the air bearing system.

VII. AROUND THE TUNNEL

The "quietest" place at CHESS is probably the point halfway down the cross-tunnel, directly in the middle of the ring. For this reason, vibration measurements that were taken in the cross tunnel serve as a good background for all other measurements taken in the tunnels.

Fig. 15: The cross-tunnel at CHESS

Synchrotron light experiments that measure the size of the electron or positron beams are located in straight sections of the beam pipe, at several points around the ring. Electrons and positrons emit visible light, as well as x-rays, as they are accelerated in a circle. This light is collected and directed out of the beam pipe by a series of mirrors, and then measured using a series of photodiodes and a camera. These set-ups are located at both ends of L3, with very long path for the light – across the room, and at 23 East and West, with a much shorter path (with tighter curves to get the light underneath the beam pipe where the optical bench is located). These mirrors can become very hot, so again, water is used to cool them. The cooling water carries vibration that could prevent an accurate measurement of the beam size.

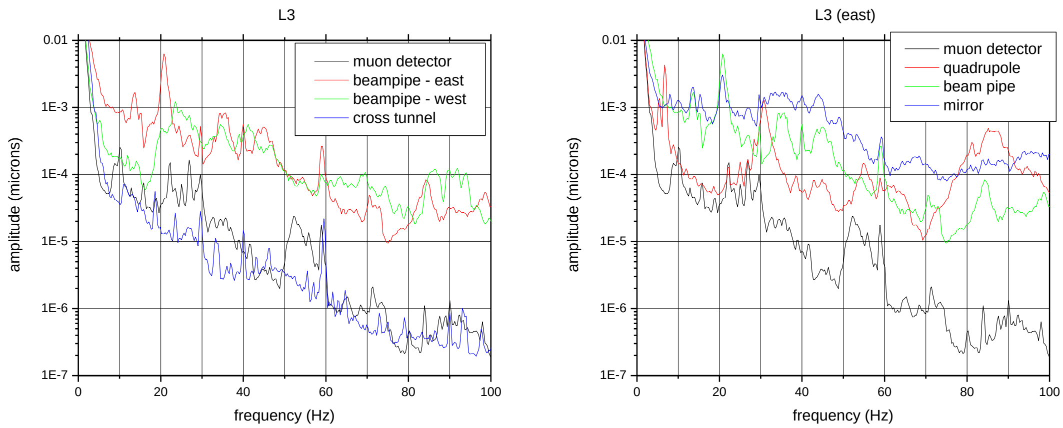


Fig. 16: Vibration measurements at L3

The beam pipe at the east end of L3 vibrates at higher amplitude than the beam pipe at the west end, for low frequencies (0-22Hz). Measurements taken on the beam pipe and on the mirror housing show similar vibration amplitudes for low frequencies. The muon detector is a good 'background' level for L3 – it vibrates only slightly more than the floor of the cross-tunnel (the quietest place at CHESS).

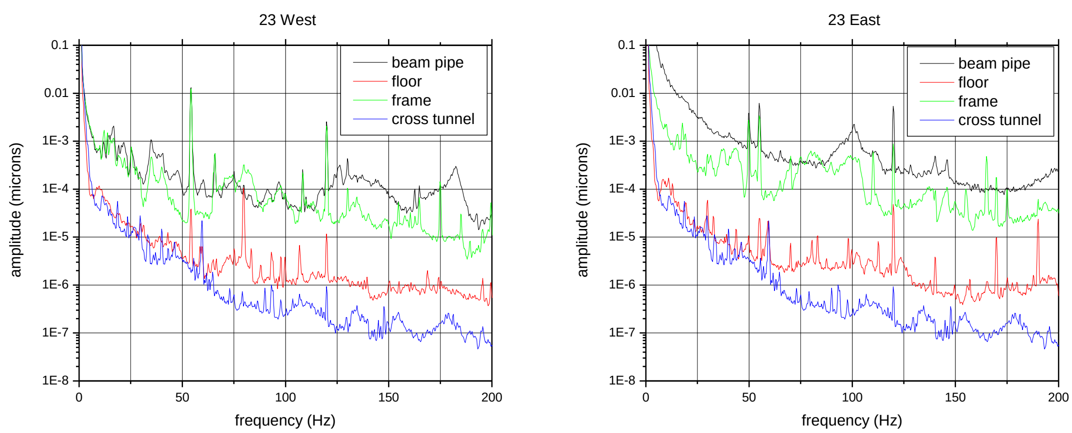


Fig. 17: Vibration measurements at 23 West and 23 East

At both 23 East and 23 West, the beam pipe vibrates the most. The east beam pipe vibrates at higher amplitude than the west beam pipe. In both cases, the frame that supports the optical elements is more stable than the beam pipe.

VIII. CONCLUSIONS AND RECOMMENDATIONS

Everything vibrates. Most vibration at CHESS appears in the fraction-of-a-nanometer range. The vibrations come from a variety of sources, from things that can be controlled (water flow rate) to things that can't be controlled (electrical noise, people walking through the hallways).

Given the success of the “vibration filter” in damping low-frequency vibrations, the installation of a similar (but more permanent) device could be explored for all systems at CHESS that rely on water cooling. This is a simple fix, but it seems to make a significant improvement.

Fig. 18: A small fleet of “vibration filters”

Further vibration analysis at CHESS is warranted. There are many systems that could benefit from more mechanical stability. The success of very simple fixes, such as the addition of a small filter into the water filter line to damp vibration in the monochromator crystals, or the addition of a triangular brace to stabilize the capillary puller [4] suggest that a relatively small amount of work could yield substantial progress toward damping the vibration. Also, vulnerability to vibration should be taken into account during the design phases of new projects, instead of waiting for problems to arise later.

IX. ACKNOWLEDGEMENTS

I would like to thank Peter Revesz and Don Hartill, both of Cornell University, for mentoring me in my project this summer. I would like to thank Robin Baur of Cornell University for her input and help on the part of my project that happened to overlap with hers. Finally, I am extremely grateful to Richard Galik, Ernie Fontes, Lora Hine, and Georg Hoeffstaetter for organizing the REU program this summer and to everyone at CHESS (especially Aaron Lyndaker, Tom Szebenyi, Eric Edwards, Darol Chamberlain, Gino Melice, Tom Krawczyk, and Sol Gruner) for their never-ending supply of answers, help, and support throughout the different stages of this project.

This work was supported by the National Science Foundation REU grant PHY-0849885.

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