LCLS-TN-23-6

SCU Guide Tube Straightness Tests

Zachary Wolf, Yurii Levashov
Stanford Linear Accelerator Center

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Abstract

Development work is underway to prepare for superconducting undulator calibration measurements. A proposed plan involves moving Hall probes through the undulator inside a stretched guide tube. For this plan to work, the guide tube must be straight in the horizontal direction to approximately 20 μm. This note documents straightness measurements on stretched guide tubes.

1 Introduction[1]

SLAC is in the process of installing a superconducting undulator (SCU) made of two segments which act as an afterburner at the end of the LCLS hard x-ray line. The SCU will act as a proof of principle test for a future SCU FEL line. The SCU must be calibrated using magnetic measurements so that it is resonant with the rest of the hard x-ray line, and also to show that magnetic measurement accuracy requirements for an FEL line can be met.

SCU magnetic measurements are difficult because the only access to the field is through the ends of the beam pipe, yet the accuracy requirements are similar to those of conventional hybrid undulators with side access to the gap. A plan for doing the SCU magnetic measurements has been proposed.[2] A key aspect of the plan is to move a Hall probe along a horizontally straight line using a stretched tube to guide the probe. The region of the SCU where the magnetic calibration tolerance is met is a horizontal region of width ± 50 μm along the undulator magnetic axis. The small width of this region is due to the short period of the SCU and the hyperbolic cosine dependence of the field profile in the horizontal direction. For accurate measurements of the K value on the straight beam trajectory through the undulator, the guide tube must also be straight to a fraction of the ± 50 μm horizontal width where the field profile is relatively flat. A key concern is whether we can guide a Hall probe on a horizontally straight line through the undulator. In this note we present measurement results of the straightness of a stretched tube, and we demonstrate that the straightness requirement can be met.

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[1] Work supported in part by the DOE Contract DE-AC02-76SF00515. This work was performed in support of the LCLS project at SLAC.

[2] Z. Wolf, "A Conceptual Plan For The SLAC Superconducting Undulator Magnetic Measurements", LCLS-TN-23-5, September, 2023.

2 Experimental Setup

The tubes used for this test have a 5 mm OD and 0.25 mm wall thickness. The tube material is 321 stainless steel. 321 stainless steel is non-magnetic, but verifying that the magnetic measurements are not affected by the stainless steel at our required level of accuracy must still be done. (Tubes made of other materials such as titanium are also being considered in case the stainless steel affects the magnetic measurements.) The tube was stretched with an Enerpac hydraulic pump, model P142, and Enerpac hydraulic hollow plunger ram, model RCH121-H. Clamps were epoxied to the ends of the tube where the forces are applied. The clamps are cylindrical in shape, split in the middle, and the two halves have epoxy applied and are bolted together around the tube. The ID of the split clamp is 5.2 mm leaving 0.1 mm around the tube for the epoxy to be at its optimal strength. The epoxy used was DP105 by 3M. A 0.1 mm spacer wire was wrapped around the tube for uniform epoxy thickness. The end of the tube with the hydraulic ram and clamp is shown in figure 1. At the other end of the tube, the clamp pushes on a fixed support.

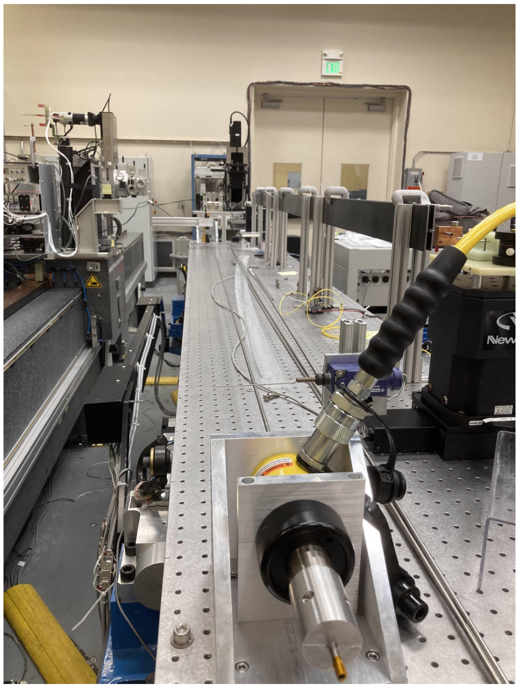

Figure 1: A hydraulic cylinder was used to push on a clamp to stretch the tube.

To stretch the tube, the pump was used to increase the pressure of the hydraulic fluid and extend the ram. The extended ram stretched the tube and increased the stress in the tube walls. When thinking about how the tube stretches, it is helpful to consider the stress-strain relation for the tube. A schematic of the stress-strain relation is shown in figure 2. Initially the stress and strain are linearly related and the tube acts like a spring up to the yield stress. Past the yield stress, as the tube is elongated, the curve becomes nonlinear and plastic deformation begins. The tube is permanently deformed at this point.

The stress in the tube reaches a maximum value at the tensile strength. Since we wanted to deform the tube to be straight, we increased the stress to the tensile strength and then further strained the tube. The tensile strength was indicated by maximizing the hydraulic pressure and noting that it did not change as the tube was elongated further.

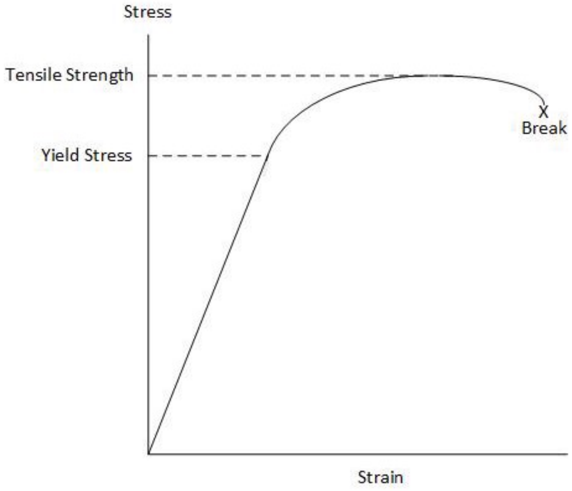

Figure 2: A schematic of the stress-strain relation for the tube.

We increased the hydraulic pressure to 146 psi. The effective push area of the ram is 2.76 sq. in. according to the data sheet. The force on the tube is then $F = 403$ pounds (1793 N). The area of stainless steel in the tube is $A = (\pi/4)((.005\text{ m})^2 - (.00475\text{ m})^2) = 1.91 \times 10^{-6}\text{ m}^2$. The stress on the tube is $\sigma = F/A = 9.4 \times 10^8$ Pa. The yield stress of the 321 stainless steel tube is $> 2 \times 10^8$ Pa and the tensile strength is 5.0×10^8 to 7.3×10^8 Pa according to the manufacturer.[3] Our measurement of the tensile strength is larger than the manufacturer's value, further confirming that we were in the plastic deformation regime.

The tube straightness measurements were made without touching the tube. The non-contact measurement was made with a laser directed onto a slit in front of a photodetector. The laser plus detector assembly was moved past the tube and the shadow of the tube changed the amount of light reaching the photodetector. A negative voltage proportional to the light intensity was recorded. The signal was later analyzed to determine the position of the tube. A schematic of the detector and output signal is shown in figure 3. A photo of the detector assembly is shown in figure 4. The assembly is moved down the tube by an undulator measurement bench. The bench is straight to approximately $\pm 5\ \mu$m. At discrete points along the tube, the detector is moved horizontally across the tube and the signal from the detector is recorded. The detector on its arm attached to the measurement bench is shown in figure 5.

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[3] The tubes were purchased from Parker Steel. The yield stress and tensile strength values came from their web site, www.metricmetal.com.

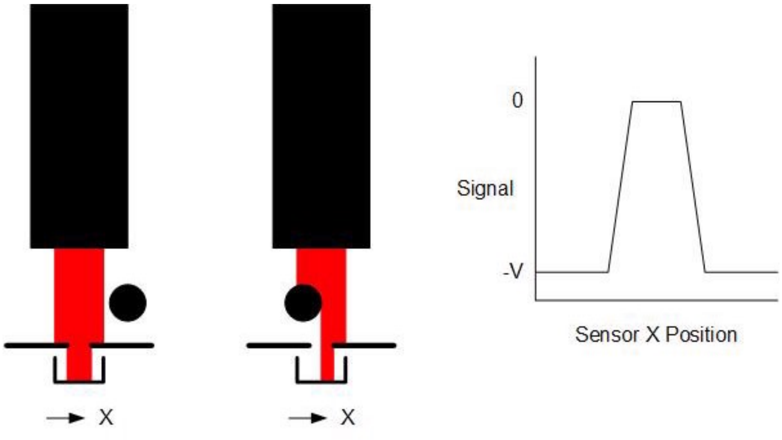

Figure 3: The intensity of laser light reaching the photodetector changes as the detector assembly moves past the tube.

Figure 4: Photo of the laser and photodetector.

Figure 5: The detector is moved by an undulator measurement bench. At discrete positions down the tube, the detector is scanned horizontally and the signal is recorded.

3 Measurement Results

3.1 Signal Profile

At 59 positions down the length of the tube, the detector was scanned horizontally across the tube. A typical signal from the detector is shown in figure 6. When the tube is not blocking the laser beam, the signal is large and negative. When the tube is fully blocking the laser, the signal is near zero with a small offset from the signal amplifier. Diffraction patterns are visible when the tube is at the edge of the slit. Lines are fit to each region of the signal profile. The lines are numbered in the figure, and the intersection points of the lines are labeled with an "x" and two numbers indicating the two intersecting line numbers.

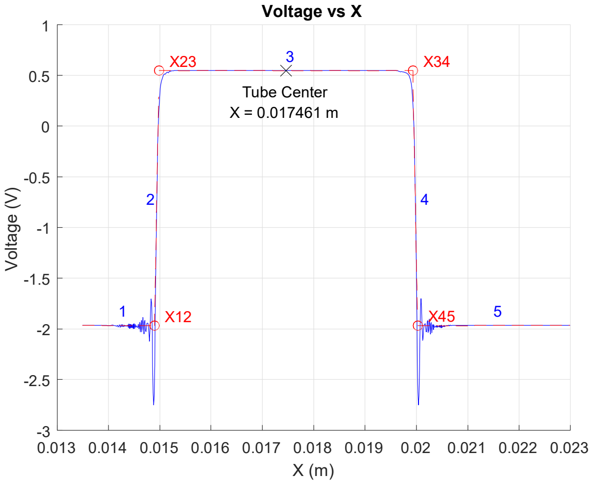

Figure 6: A typical signal from the detector as it is scanned across the tube.

The x-positions of the intersection points are used to find the x-position of the center of the tube, and they also give a measurement of tube diameter variations. The position of the detector in each linear region and at the intersection points is shown in figure 7. The center of the tube is given by the mean of the x-positions of the pairs x12 and x45, and also by the mean position of the pairs x23 and x34. When these measurements are averaged, the center position is most accurately given by the mean of all four intersection points x12, x23, x34, and x45. The diameter of the tube is given by the distance the detector moves between points where the leading and trailing sides of the tube are at the same edge of the slit. This is the distance between x-positions x12 and x34, or x23 and x45.

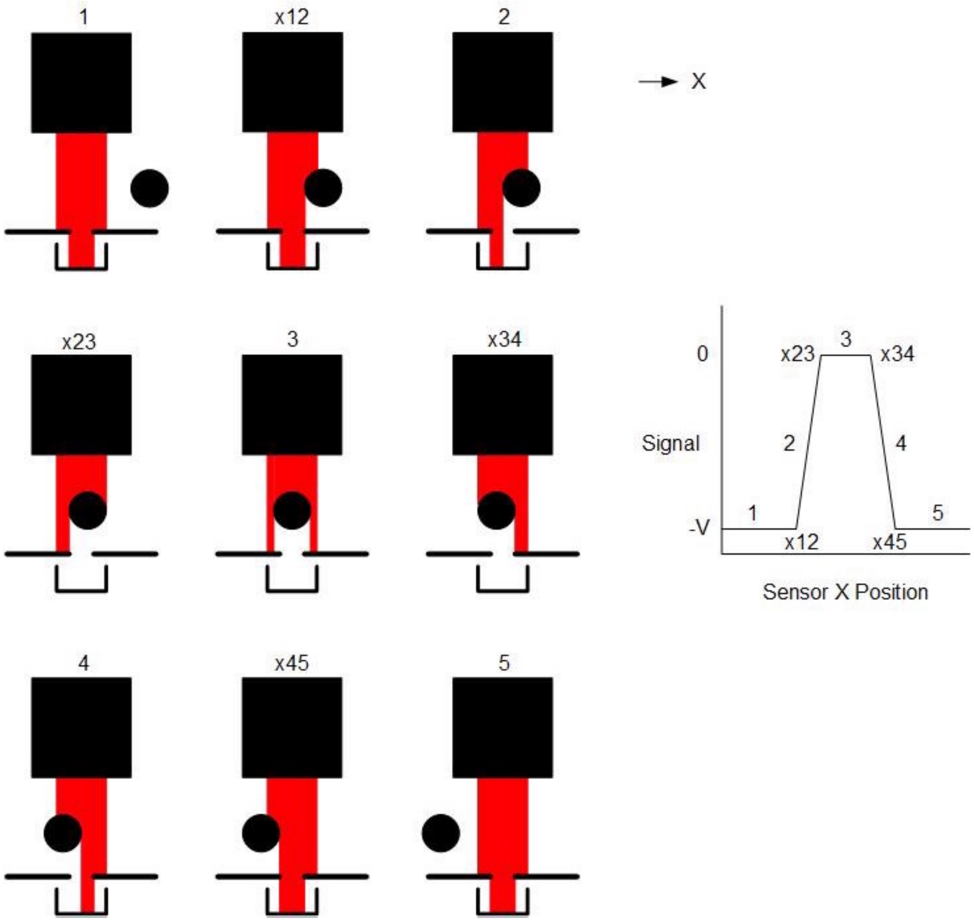

Figure 7: Position of the detector in each linear region and at the intersection points.

3.2 Tube Diameter

The intersection points of the five lines fit to the signal profile are used to measure the tube diameter and its variation. Figure 8 shows the x-position of points x12, x23, x34 and x45 along the tube. The tube is not parallel to the bench, so the x-positions change along the tube. The difference in the x-positions x34 - x12 and x45 - x23 give two measurements of the diameter of the tube. Figure 9 shows the two measurements of the diameter and they agree well. If one averages the two measurements and subtracts the mean, one is left with the deviations in the tube diameter. Deviations in the diameter of the tube are shown in figure 10. The tube diameter variations are below 10 μm.

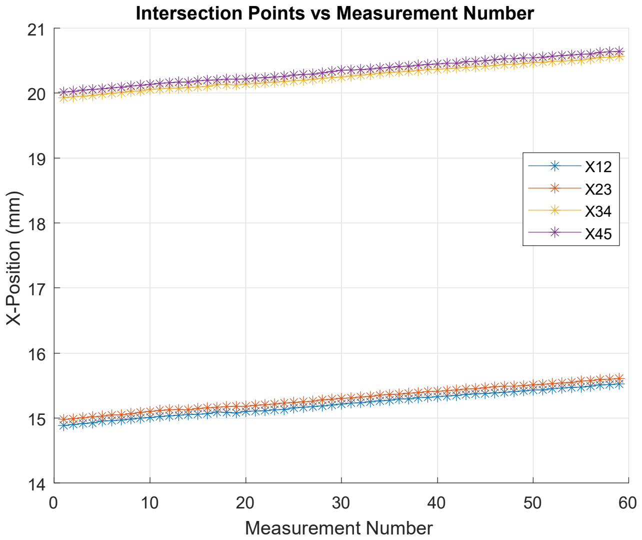

Figure 8: X-positions of the intersection points of the linear fits to the signal profile.

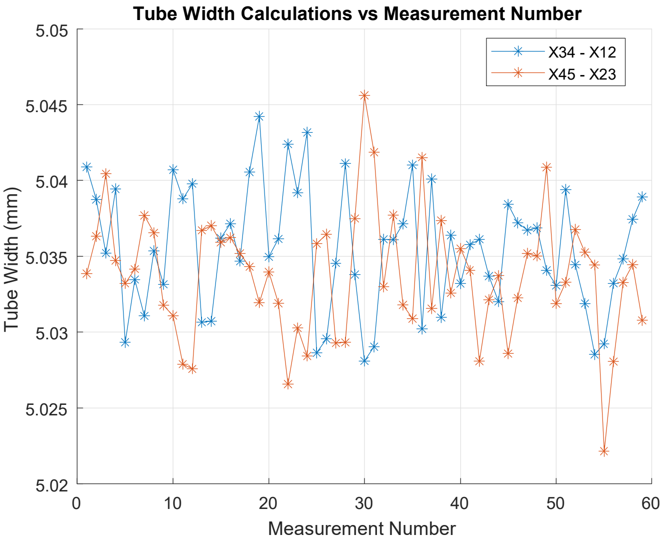

Figure 9: The tube diameter is given by differences in the x-positions of the intersection points of the lines fit to each region of the signal profile.

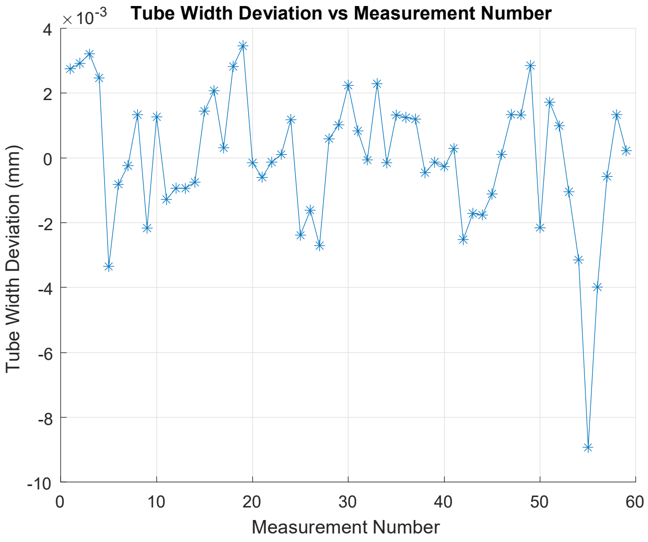

Figure 10: Deviations in the diameter of the tube.

3.3 Tube Straightness

Two measurements of the center position of the tube are given by the mean of x23 and x34, and by the mean of x12 and x45. These measurements agree as shown in figure 11. Figure 12 shows the tube center position calculated as the mean of x12, x23, x34, and x34, and a linear fit. The residuals of the fit give the tube straightness deviations. The residuals are shown in figure 13. The tube is straight to ±15 μm.

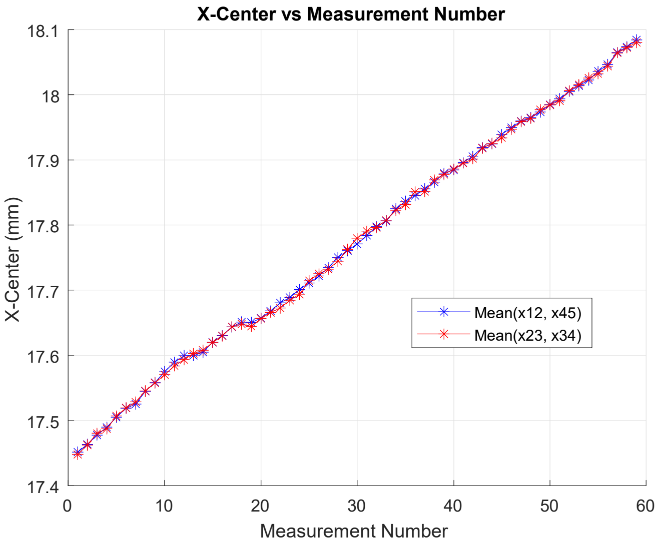

Figure 11: The tube center position is calculated as the mean of x12 and x45, and as the mean of x23 and x34.

Two different tubes were stretched and had measurements made of the tube straightness. The results from the second tube are shown in figure 14. This tube is not as straight as the first, but still is straight to approximately ±20 μm.

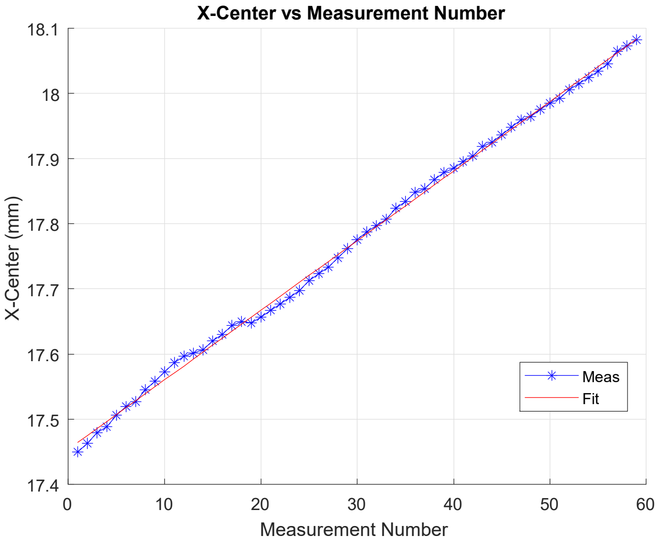

Figure 12: Tube center position measured along the tube and a linear fit.

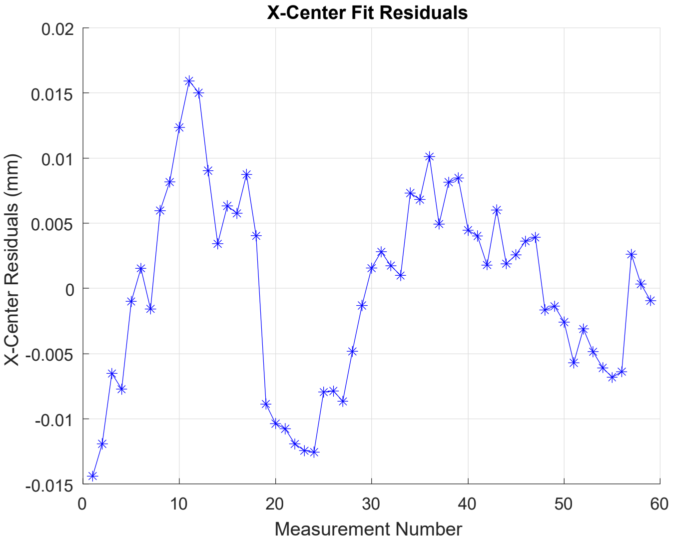

Figure 13: The tube is straight to ±15 μm.

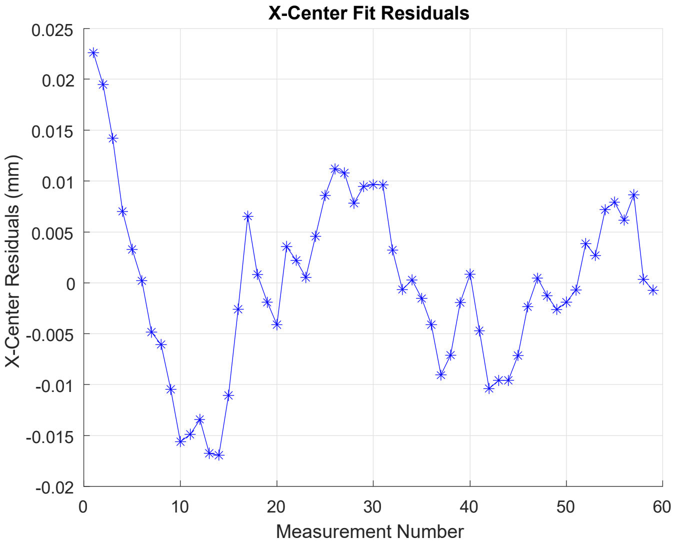

Figure 14: Straightness measurements on the second tube. The tube is straight to approximately ±20 μm.

3.4 Tube Sag

An alignment crew made measurements of the vertical position of the tube. The results are shown in figure 15. The setup is not level which accounts for the average slope of the measurements. If one draws a line between the end points and subtracts the line from the measured vertical positions, one gets the results shown in figure 16. The tube sag is approximately 300 μm.

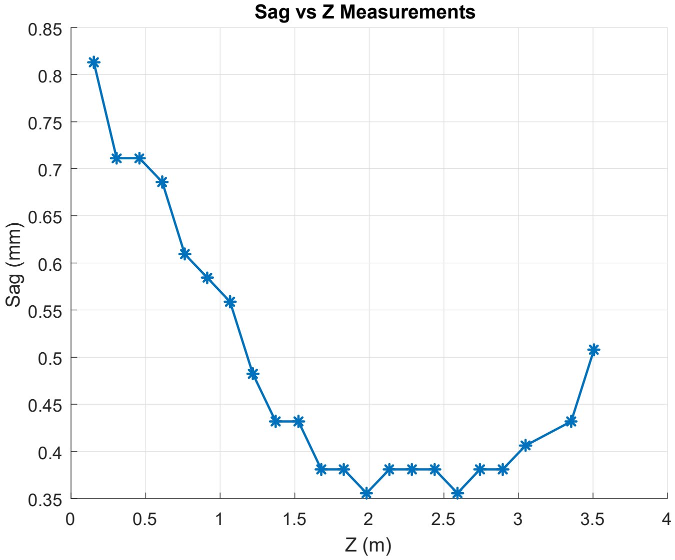

Figure 15: Measurements of the vertical position of the tube.

4 Further Development Work

We have demonstrated that by stretching a thin wall tube, it is made horizontally straight to approximately ±20 μm. This meets our requirement for the straightness of the line our Hall probe must follow for SCU magnetic measurements. Further development work on the guide tube must include the following:

321 stainless steel is non-magnetic, although this claim has not been quantified. We must verify that a 321 stainless steel tube will not affect our measurements. This will be done in a calibration magnet. We will calibrate the Hall probe up to the maximum 1.6 T field of the SCU. Then we will repeat the calibration with a 321 stainless steel tube around the probe. Differences in the calibrations will determine if the measurements will be affected at the 10^{-4} level. If the measurements are affected, we must switch to another material for the guide tube. Titanium is a possible alternate choice.

Another concern is whether moving the probe tube longitudinally moves the guide tube transversely. This might happen because of vibrations or because of a bend in the probe tube. We will test this by placing the optical detector so that the shadow of the tube covers half the slit. If the guide tube moves horizontally as the probe tube is inserted or

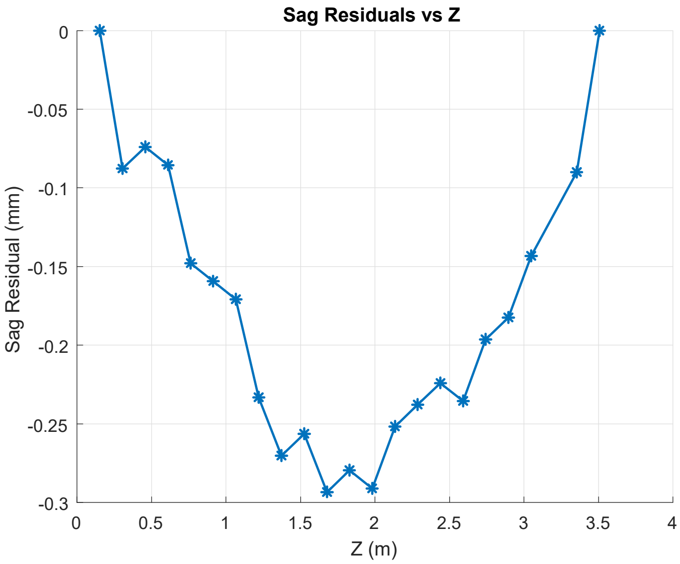

Figure 16: Measured sag of the tube.

removed from the guide tube, the signal from the detector will change and give a measure of the amount of horizontal motion.

5 Conclusion

A plan to calibrate upcoming SCUs relies on moving a Hall probe on a line horizontally straight to better than ±50 μm. The plan envisioned a stretched guide tube which is horizontally straight to approximately ±20 μm. Testing whether this is possible is the purpose of this note. We found thin wall, non-magnetic stainless steel tubes of about the right diameter. We devised a way to stretch the tubes and measure their straightness in a non-contact manner. We found that stretching thin wall tubes straightens them in the horizontal direction so straightness deviations are approximately ±20 μm. Stretching also reduces the sag to approximately 300 μm.