

Design of a low-temperature scanning tunneling microscope head with a low-friction, piezoelectric coarse approach mechanism

T. A. Smith¹ and A. Biswas²

¹*Department of Physics, Southern Illinois University Edwardsville, Edwardsville, Illinois 62026, USA*

²*Department of Physics, University of Florida, Gainesville, Florida 32611, USA*

We describe the design of a low-temperature scanning tunneling microscope (LT-STM) head with an integrated piezoelectric coarse approach mechanism. The friction-based motor is tested at room-temperature, and the friction-level is optimized to allow the device to operate reliably at peak voltages down to ± 110 V. We discover that, in a low-friction configuration, the step-size of the motor depends on its orientation with respect to the Earth's gravitational field.

I. INTRODUCTION

Low-temperature scanning tunneling microscopy is a powerful technique for studying surface phenomena that only occur at low temperatures, but the technique is difficult and has several requirements. The coarse approach mechanism of a low-temperature scanning tunneling microscope (LT-STM) must be able to position the scanning tip towards the sample in steps smaller than the longitudinal range of the piezoelectric scanner (typically 10-100 nm at liquid helium temperatures).^{1,2} This has routinely been achieved via piezoelectric actuation processes that, while sensitive to changes in temperature, allow one to control the mechanism as it rests in a cryostat.^{3,4} LT-STM experiments, which typically operate in the temperature range from 4.2 to 300 K, are useful for studying periodic and non-periodic features of material surfaces – such as quantum vortices in high- T_c superconductors and charge ordering in mixed-valence manganites.⁵⁻⁷ Furthermore, experiments requiring real-space, high-resolution surface

measurements benefit from LT-STM techniques because the low-temperature conditions reduce thermal drift and thermal noise.³

A typical LT-STM head incorporates a piezoelectric tube scanner and a coarse approach mechanism into a main body.^{3,4,8} This design is compact and rigid, making it suitable for use in refrigeration units with limited space and vibrational noise. The coarse approach motor can be composed of six shear piezos that position the scanner-holder using a friction-based actuation mode.^{3,4,9} For a given level of friction, the amplitude of the voltage signal applied to the piezos determines the step-size of the motor, and this value is typically between 200 and 400 V. Several studies report that this mode, operating at low-temperatures, leads to reproducible step sizes that are relatively insensitive to the orientation of the LT-STM head with respect to the gravitational field of the Earth.^{3,9}

Currently, however, there are only three groups in the United States that consistently publish LT-STM studies of novel materials.¹⁰⁻¹² It is possible that the scarcity of this research is due, in part, to its inherently precarious nature. High-voltage signals can damage or destroy piezoelectric components and produce sparks in dry environments. Here, we analyze the step-size of a home-built LT-STM coarse approach mechanism in a low-friction state with operating voltages between 184 and 110 V. We report that, in this state, the step size is strongly dependent on the orientation of the coarse approach mechanism with respect to the Earth's gravitational field. We conclude that the weight of the scanner holder is an important consideration when constructing a low-friction LT-STM motor.

II. EXPERIMENTAL DETAILS

Rhinoceros 3D modeling software (version 4.0) was used to design the LT-STM head (shown in Fig. 1). All pieces were machined from brass except for the piezoelectric components, the sapphire plates, and the compression plate. The LT-STM head was constructed without the sample holder, piezo tube scanner, or optional wire guide to test the functionality of the coarse approach mechanism under various conditions. In its assembled state the LT-STM head has dimensions of 3.25 in. height and 1.5 in. in diameter.

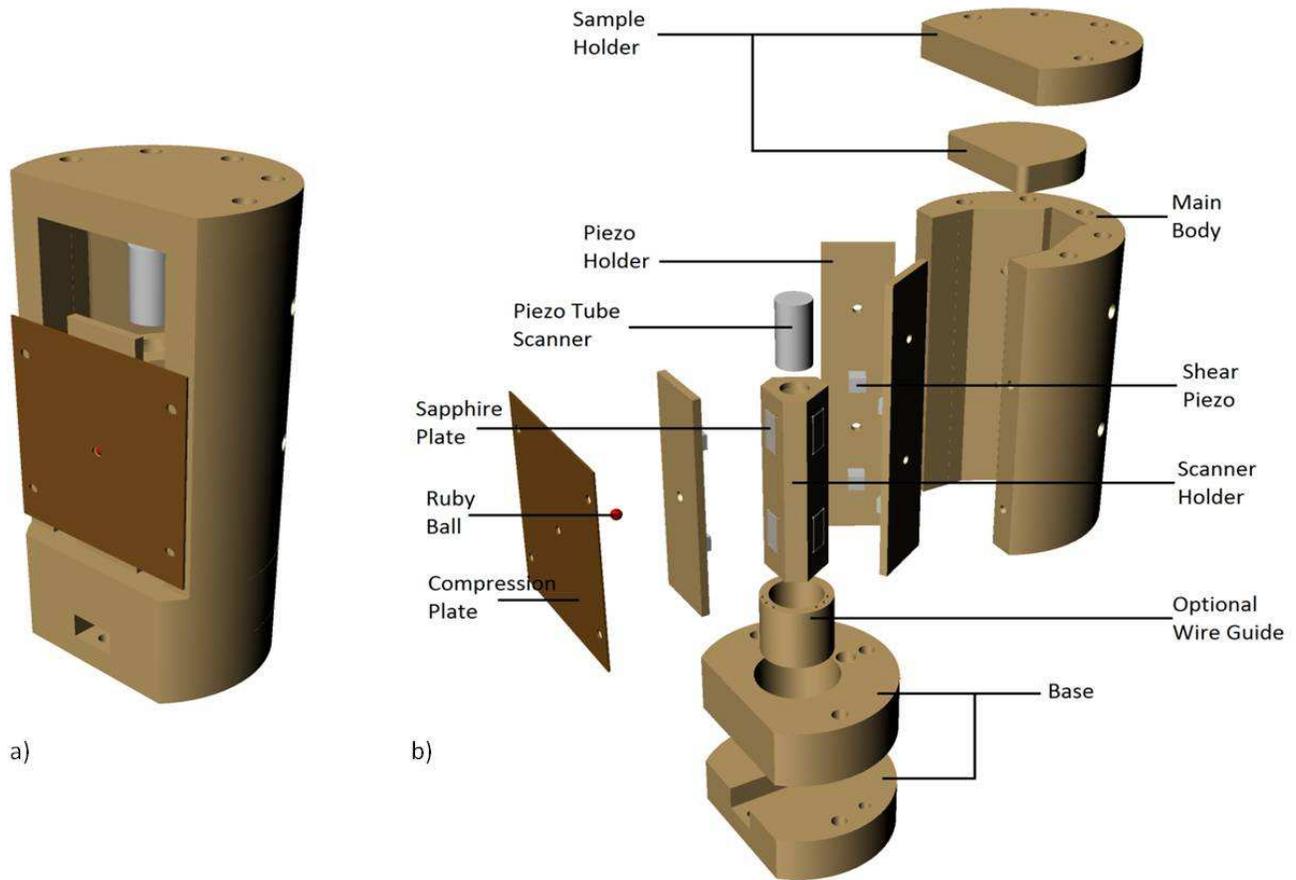


FIG 1. 3D models of the LT-STM head created using Rhinoceros modeling software. (a) View of the LT-STM head in its assembled state. (b) Components of the LT-STM head.

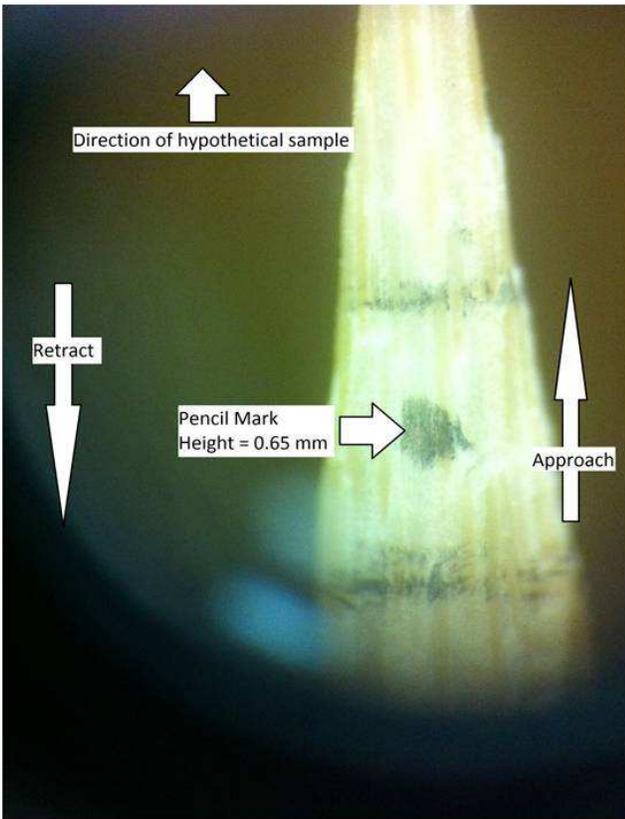


FIG 2. A wooden applicator stick was attached to the scanner holder and marked with a pencil. For an actual measurement, the mark was positioned at the bottom of the viewing area. A telescopic lens was used to monitor the time, Δt , required for the mark to disappear or appear when the scanner holder was retracting or approaching respectively. The average velocity, v_{av} , of the scanner holder can then be computed from $v_{av} = h / \Delta t$, where h is the height of the pencil mark.

Motion of the central scanner holder was achieved via six shear piezos that were connected to separate output channels of a home-built pulse sequence controller (PSC). The PSC can output a periodic series of pulse sequences for continuous motion. The output of the PSC is modified by a set of keyboard commands that are sent to the device's microcontroller via a RS-232 serial interface. This allowed us to change the signal frequency, amplitude, and polarity. We fastened a seven-pin connector to the base of the LT-STM head with epoxy gel and soldered one wire from each of the six shear piezos to separate terminals (the seventh terminal was used as a common ground). This allowed us to connect the output of the pulse sequence controller to the LT-STM head with one connector. The actuation process is common to LT-STM devices and has been described in detail elsewhere.^{3,4,8,9} A unique feature of our PSC is the high frequency of the pulses. The polarity of the signal from the PSC determines the direction of motion. Fig. 2 describes the method used to measure the average bidirectional velocity, v_{av} of

the scanner holder. The approximate step size of the actuator, Δz , was determined using the relation,

$$\Delta z = \frac{v_{av}}{f} \quad (1)$$

where f is the frequency of the signal from the PSC.

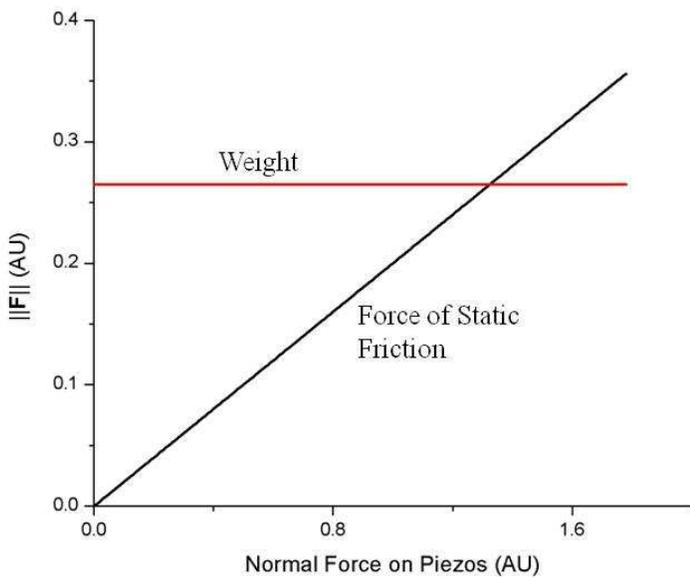


FIG 3. Tightening the compression plate bolts increases the normal force on the shear piezos. The magnitude of the static frictional force on the piezos is proportional to the normal force, and the scanner holder is held in place when the static frictional force is equal to its weight (this occurs at the intersection of the two lines above). To minimize the friction for low driving voltages, our measurements were taken for compression plate settings that marginally surpassed this minimum frictional requirement.

The friction between the shear piezos and the sapphire plates on the scanner holder keeps the scanner holder in place as long as the compression plate is fastened to the main body. The compression plate is attached with four bolts, and it is separated from the front piezo plate by a ruby ball that distributes the pressure evenly across all six piezos. Thus, the friction between the shear piezos and the scanner holder can be adjusted by tightening one or more of the compression plate screws (Fig. 3). We measured the step-size of the motor at several different

levels of friction by turning one screw by $\theta = 45^\circ$ to increase the pressure exerted by the compression plate for each level. This was done for motion perpendicular and parallel to the gravitational field of the Earth at room-temperature.

III. RESULTS

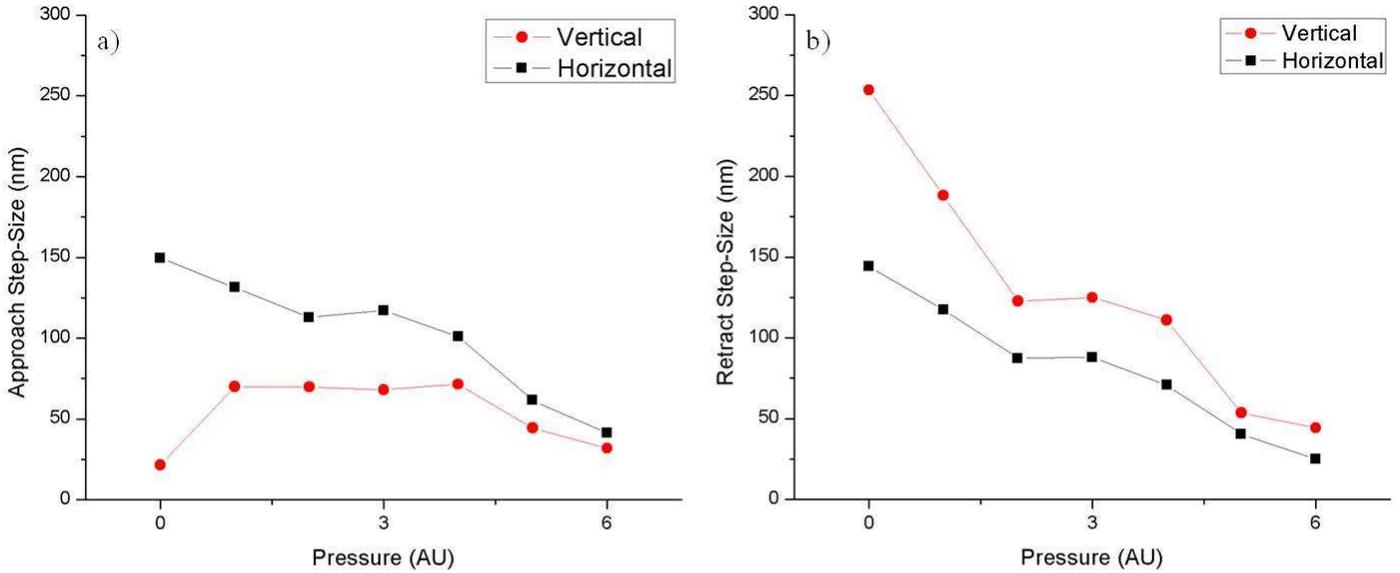


FIG 4. Step-size measurements for LT-STM head orientations perpendicular (Horizontal) and parallel (Vertical) to the Earth's gravitational field. One unit of pressure corresponds to a 45° turn of one compression plate bolt. (a) Coarse approach mechanism approach cycle, operating at 303 Hz with a peak voltage of -184 V. (b) Coarse approach mechanism retract cycle, operating at 303 Hz with a peak voltage of 184 V.

The step-size of the coarse approach motor depends strongly on the friction between the shear piezos and the scanner holder (Fig. 4). When the motor is moving horizontally or in the same direction as the Earth's gravitational field, the step-size decreases by an order of magnitude after six successive levels of increasing pressure; after which, motion ceases altogether. When

the motor is accelerating against the Earth's gravitational field, the data show a sharp increase in the step-size between the 0 and 1 pressure settings. Also, at each pressure setting there is a discrepancy between the horizontal and vertical step-sizes, but the two curves begin to converge as the pressure is increased. For the approach cycle, this discrepancy ranges from 128 nm at the lowest pressure level to 9 nm at the highest pressure level (Fig. 4(a)).

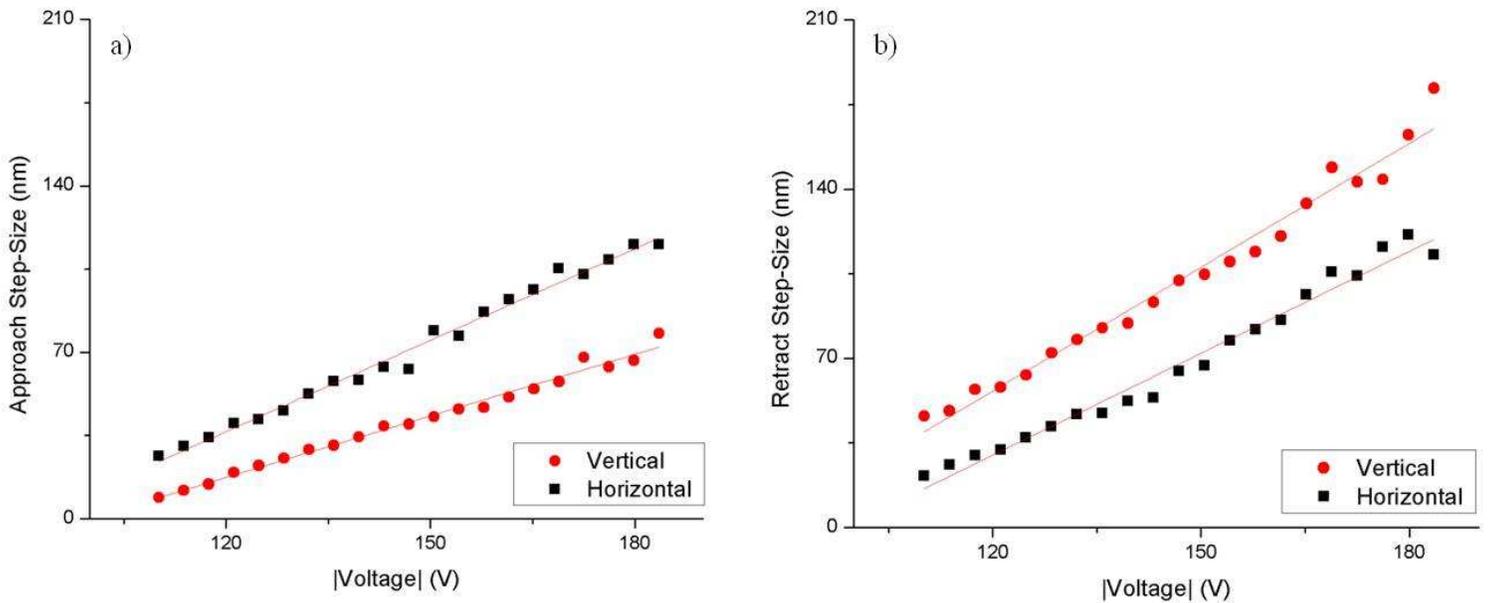


FIG 5. Step-size versus voltage measurements for vertical and horizontal orientations. The absolute value of the voltage is on the abscissa axes to ignore polarity. a) Approach cycle operating at 303 Hz and pressure level 3. b) Retract cycle operating at 303 Hz and pressure level 3.

The step-size of the motor depends linearly on the peak voltage of the pulses sent to the piezos (Fig. 5). The motor stops functioning reliably below a peak voltage of ± 110 V, and the maximum peak voltage (± 183 V) is limited by the PSC. For the approach cycle (Fig. 5(a)), the slopes of the vertical and horizontal mode fits are 1.28 nm/V and 0.82 nm/V respectively. For

the retract cycle (Fig. 5(b)), the slopes of the vertical and horizontal mode fits are 1.71 nm/V and 1.41 nm/V respectively.

IV. DISCUSSION/CONCLUSION

To our knowledge, no other studies involving a LT-STM head with a piezoelectric coarse approach mechanism have reported the dependence of the step-size on the amount of pressure applied to the piezos. Our data indicate that the step-size of the low-friction motor constructed in this study is strongly susceptible to small changes in the friction between the piezos and the scanner holder. Also, when the device is operating within its functional limits (between 0 and 6 pressure units), its step-size depends on its orientation with respect to the Earth's gravitational field. In fact, we were forced to redesign a lighter scanner holder because our initial design was too heavy and could not accelerate against the Earth's gravitational field. Mariotto *et al.* report that, for their piezoelectric walker, the step-size is unaffected by gravity.⁹ However, this is not in contrast to our results because their operating voltages ranged from 190 V to 400 V, and their step size range is similar to ours. Since their design is similar to ours, this could indicate that the pressure applied to the piezos was much higher in their device. Furthermore, the discrepancy in step-size between the horizontal and vertical orientations decreases as the piezo friction is increased, leading us to believe that a high-friction device, operating at much higher voltages, would lose this gravitational dependence.

Several studies on piezoelectric coarse approach mechanisms report a linear dependence of the step-size on the voltage applied to the piezoelectric element(s), and our data corroborate this (Fig. 5).^{1,2,9} However, the voltages at which our device functions reliably are less than those reported by similar studies which have reported peak voltages of 300 V and 400 V.^{3,4} An

exception to this is the work done by Blackford and Jericho, but their actuation method, which involves a piezoelectric tube instead of six shear piezos, differs significantly from ours.² Further testing is required to determine if the low-friction configuration of our LT-STM coarse approach motor is suitable for low-temperature actuation (down to 4.2 K).

ACKNOWLEDGEMENTS

This work is supported by DMR-9820518, DMR-0139579, DMR-0552726, and DMR-0851707. We would like to thank John Timmerwilke for helpful discussions and the members of the University of Florida physics machine shop for their collaboration in creating the various STM components.

REFERENCES

- ¹I. B. Altfeder and A. P. Volodin, Rev. Sci. Instrum. **64**, 3157 (1993).
- ²B. L. Blackford and M. H. Jericho, Rev. Sci. Instrum. **61**, 182 (1990).
- ³S. H. Pan, E. W. Hudon, and J. C. Davis, Rev. Sci. Instrum. **70**, 1459 (1999).
- ⁴C. Wittneven, R. Dombrowski, S. H. Pan, and R. Wiesendanger, Rev. Sci. Instrum. **68**, 3806 (1997).
- ⁵R. Wiesendanger, *Scanning Probe Microscopy and Spectroscopy: Methods and Applications* (Cambridge University Press, Cambridge, 1994).
- ⁶Y. Yin et al., Phys. Rev. Lett. **102**, 097002-1 (2009).
- ⁷C. Renner et al., Nature **416**, 518 (2002).
- ⁸D. Wehnes, J. Meier, J. Classen, and C. Enss, Appl. Phys. A **66**, S41 (1998).
- ⁹G. Mariotto, M. D'Angelo, and I. V. Shvets, Rev. Sci. Instrum. **70**, 3651 (1999).
- ¹⁰J. A. Gupta, C. P. Lutz, A. J. Heinrich, and D. M. Eigler, Phys. Rev B **71**, 115416-1 (2005).
- ¹¹A. R. Schmidt et al., New J. Phys. **13**, 065014 (2011).
- ¹²C. V. Parker et al., Nature **468**, 677 (2010).