

# Design and development of a low temperature STM with an XY coarse stage

BACHELOR THESIS

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## **Preface and Acknowledgement**

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## Abstract

Scanning tunneling microscopy is an important and enabling tool for condensed matter physics and surface science. The low temperature STM in Leiden (Prof. J. Van Ruitenbeek and Prof J. Aarts) is used for research in the field of atomic/molecular electronics and superconductivity. The current low temperature STM head can scan an area of 300 nm by 300 nm. Sometimes the scanned surface of the sample is not suited to perform a measurement: it can be locally too rough, or contaminated, or the STM probe (the “tip”) is just not within range of the region of interest. For this a coarse stage is needed that will move the sample to a new position to scan. Such a coarse stage was not implemented in the current STM.

The new design will have the same Z motor<sup>1</sup>, because the current Z motor functions well and is compact (In this Z motor the Z coarse and fine stage are combined). The XY motor should not rotate or vibrate<sup>2</sup>. The new XY motor will also house a new sample holder which will allow two separate currents through the sample, as this is required for future experiments.

The current motor is inspired by a well-established low temperature design by Pan *et al*, but was adapted to achieve a more compact and rigid microscope. The new design is also based on the Pan design, but the challenge is to adapt it again in order to make it very compact (because of the small space). All of this without compromising in rigidity and temperature stability.

In this work we discuss several concepts (see appendix C) with their advantages and disadvantages and we motivate the choice (for a particular and promising design see chapter 3). For two of the concepts resonance frequencies have been calculated with Comsol Multiphysics<sup>tm</sup>. Also for the most important design an electrodynamic calculation has been made.

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<sup>1</sup> The function of the Z-motor is to bring the tip and the sample in tunneling regime and to follow the surface during imaging.

<sup>2</sup> The quantitative definition of maximum allowed rotations/vibrations will be given in the report.



# Table of Contents

<b>Preface and Acknowledgement</b>	<b>iii</b>
<b>Abstract</b>	<b>v</b>
<b>List of Abbreviations</b>	<b>ix</b>
<b>List of Figures</b>	<b>x</b>
<b>1. Introduction</b>	<b>1</b>
1.1 Electron tunneling	1
1.2 The current STM	2
1.3 Motivation	3
<b>2. Piezoelectric motor</b>	<b>5</b>
2.1 Piezoelectric elements	5
2.2 Slip-Stick motion	5
2.3 Driving signal	6
2.3.1 The coarse stage	6
2.3.2 The fine stage	7
<b>3. STM Design</b>	<b>9</b>
3.1 Design requirements	9
3.2 The principle of the design	10
3.3 CAD drawings of the design	10
3.4 The new sample holder	11
<b>4. FEM calculations</b>	<b>13</b>
4.1 Resonance frequency analysis	14
4.2 Electrodynamic calculations	15
4.2.1 Z stage	15
4.2.2 Z stage with grounding plate	17
4.2.3 XY stage	18
<b>5. Conclusion</b>	<b>19</b>
<b>Bibliography</b>	<b>20</b>

<b>Appendix A: Z motor by Pan Design</b>	<b>21</b>
<b>Appendix B: Piezoelectric effect</b>	<b>22</b>
<b>Appendix C1: Design 1 ‘The wire design’</b>	<b>23</b>
<b>Appendix C2: Design 2 ‘The bearing design’</b>	<b>24</b>
<b>Appendix C3: Design 3 ‘The Greek temple design’</b>	<b>25</b>
<b>Appendix D: The original assignment</b>	<b>26</b>

## List of Abbreviations

AFM	Atomic Force Microscopy
CAD	Computer-Aided Design
FEM	Finite Elements Method
PZT	Lead Zirconate Titanate, $\text{Pb}(\text{Zr}_x\text{Ti}_{1-x})\text{O}_3$
STM	Scanning Tunneling Microscope
UHV	Ultra High Vacuum

## List of Figures

Figure 1.1: Simplified representation of a typical STM [3].	1
Figure 1.2: A representation of the energy levels between the tip and the sample.	2
Figure 1.3: A schematic drawing of the current STM, both Z and XY stage. The STM body is made of Titanium, the stacks are made of PZT for low temperature operation and the spring is made of beryllium copper [4].	2
Figure 2.1: Simplified representation a shear piezo element. The dotted lines represent the displacement when a voltage is applied. The voltage is applied over the bottom and top of the piezo [6].	5
Figure 2.2: An illustration of the slip-stick motion. The four blocks on the sides represent the piezo stacks and the block in the middle represents the slider [5].	5
Figure 2.3: (a) The Z approach signal, consisting of a driving pulse (seen as the spike) and a slow voltage ramp. (b) The driving pulse, a half parabola with a sharp cutoff [4].	6
Figure 3.1: A simplified representation of the design. 1 is the piezo stack, 2 is the moving disc and 3 is the sample holder.	10
Figure 3.2: A schematic drawing of the design. The radius is 16.4 mm and the height is 81.3 mm. a) The whole STM. b) Top part of the XY fine and coarse stage. c) Bottom part of the XY fine and coarse stage. More about the grounding plate in paragraph 4.2.	10
Figure 3.3: Schematic drawing of the new top part of the XY stage.	11
Figure 3.4: Schematic drawing of the current sample holder and mount. Sample is down facing the tip which points up in this STM (see Figure3.2).	11
Figure 3.5: Schematic drawing of the new Sample holder and mount.	12
Figure 4.1: A schematic drawing of the resonance frequency analysis model. All the inessential parts are left out of the model.	14
Figure 4.2: The calculated displacement of the 12.16 kHz resonance frequency. Dark blue means no displacement and dark red means the maximum displacement. The wire-frame blocks show the original position of the model.	14
Figure 4.3: A schematic drawing of the used Z stage model for the electrodynamic calculation.	15
Figure 4.4: The calculated electric potential over time by the tip holder. The black points are the calculated points and the red line is a sinusoidal fit.	16
Figure 4.5: A schematic drawing of the used Z stage with grounding shield model for the electrodynamic calculation.	17
Figure 4.6: The calculated electric potential over time by the shielded tip holder. The black points are the calculated points and the red line is a sinusoidal fit.	17
Figure 4.7: A schematic drawing of the used XY stage model for the electrodynamic calculation.	18
Figure 4.8: The calculated electric potential over time by the sample holder. The black points are the calculated points and the red line is a sinusoidal fit.	18

# 1. Introduction

In 1981 the first STM was invented by Gerd Binnig and Heinrich Rohrer, who won the Nobel Prize for this reason. Throughout the years this instrument has proven to be a powerful tool for various disciplines in physics, chemistry and biology. The STM can reveal the local atomic structure of a conducting surface by resolving the local electron structure. The investigation of the local atomic structure and of the density of states of the electrons is of great importance for the condensed matter research groups [1].

The STM-microscope uses a metallic sharp tip as probe to image the sample as shown in figure 1.1. The tip consists of metallic wire which is sharpened mechanically or electrochemically. By positioning the tip close to the sample, in the order of a few ångströms, and applying a voltage bias between the tip and sample an electric current will flow. This current is the result of a quantum-mechanical phenomenon: electron tunneling [2] [3].

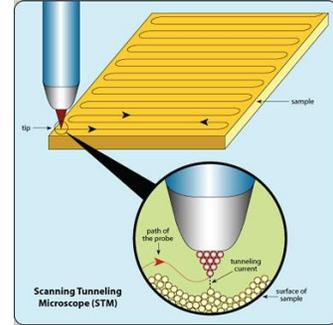


Figure 1.1: Simplified representation of a typical STM [3].

## 1.1 Electron tunneling

In classic mechanics, assume an electron with energy  $E$  moving in a potential  $U(z)$ . In the case when  $E > U(z)$ , the electron will be able to overcome the potential with a nonzero momentum  $p$ . When  $E < U(z)$ , the electron cannot move through the potential (also known as a Potential barrier) [2].

In quantum mechanics, the state of this electron is described by a wave function  $\psi(z)$ . In the case when  $E > U(z)$ , the solution of the wave function will give the electron either a positive or negative momentum (the same as in the classic case). However for the case when  $E < U(z)$ , the wave function has the following solution [2]:

$$\psi(z) = \psi(0)e^{-kz} \quad (1)$$

where  $k$  is the decay constant. This decay constant describes a state of the electron decaying in the  $+z$  direction. The probability density of observing an electron near point  $z$  is proportional to  $\psi^2(z)$ , which has a nonzero value in the potential barrier. This means that there is a nonzero probability for the electron to penetrate the barrier [2].

The height (minimal energy to overcome) of the potential barrier at the STM is the work function of the metal (a few eV for typical metals). This work function is defined as the minimal energy required for removing an electron from the surface. Its height depends on the material and the crystal structure at the surface. STM is often performed in UHV, which means that in the area between the sample and tip there are almost no other gas atoms around that may function as another potential barrier. The width of the barrier is the distance between the tip and the sample. The electrons in the tip can tunnel to the sample and vice versa. Yet there is no net tunneling current [2].

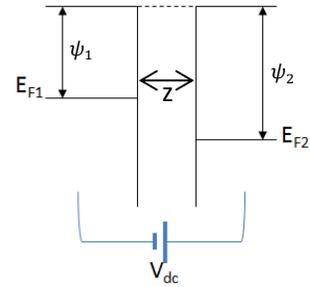


Figure 1.2: A representation of the energy levels between the tip and the sample.

By applying a bias voltage  $V$  between the tip and the sample, a net tunneling current occurs. However the energy of the electron is much smaller than the work function. Therefore the net tunneling current will be very small (in the range of several nA). The energy levels between the tip and the sample are shown in figure 1.2. Note the bias voltage that is applied between the tip and the sample. Because of the exponential dependence of the tunneling current on the tip-sample separation, STM is a very sensitive tool and can routinely achieve atomic resolution on electrically conducting surfaces [2].

## 1.2 The current STM

Conceptually an STM can be divided in a coarse stage and a fine stage. For the Z (vertical) stage the coarse stage is used to bring the tip close enough for the tunneling current (the approach), while the fine stage is used to adapt the height of the tip while scanning. The sample of the current STM is movable in the X and Y (horizontal) directions, but only for the scan motion (the fine stage). The scan motion is a raster as depicted in figure 1.1. While the tip moves in the X and Y direction with such a zig-zag motion, the image is acquired by monitoring the tunneling current by a set point. This set point is kept constant by the feedback electronics. To keep it constant, the tip position is changed up and down accordingly by moving the Z, thus following the surface. For all the movements, piezoelectric stacks are used. In Chapter 2 of this thesis there is a detailed explanation on this subject [4].

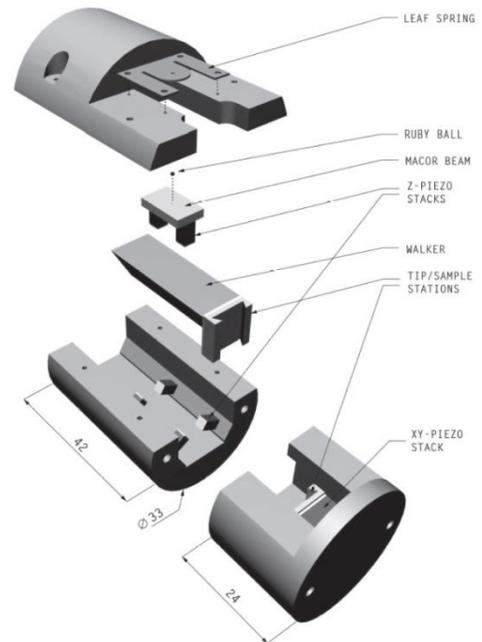


Figure 1.3: A schematic drawing of the current STM, both Z and XY stage. The STM body is made of Titanium, the stacks are made of PZT for low temperature operation and the spring is made of beryllium copper [4].

A CAD-drawing of the current STM is shown in figure 1.3. The upper part is the Z coarse and fine stage that is housing the tip, and the lower part the XY coarse and fine stage that is housing the sample. In the setup the STM is mounted vertical with the Z-stage on the bottom. An explanation of the functionality of the Z stage is found in appendix A [4].

In order for the experiments to succeed the STM operates in UHV, low temperatures (300 mK) and high magnetic fields (up to a maximum of  $\pm 10$ T). Because of these features the material choices are limited. The materials have to be non-outgassing, non-magnetic, have a high thermal conductivity and have about the same thermal expansion coefficient as titanium. The latter material property is required because the housing of the STM is made of titanium and while cooling down the dimensions should remain proportional<sup>3</sup>.

The maximum size of the STM body is limited by the housing, which has to fit into a bore of a superconducting magnet. This housing is a cylindrical tube, with room for a STM with a height of 118 mm and a radius of 16.4 mm. The current STM is shorter than this height, so it is enclosed between two copper cylindrical spacers.

### 1.3 Motivation

The current temperature STM is a low temperature STM, the head of the STM can scan an area of 300 nm by 300 nm. Sometimes the scanned surface of the sample is not suited to perform a measurement: it can be locally too rough, or contaminated, or the tip is just not within range of the region of interest. To solve this problem an XY coarse stage is required, such a stage is not yet implemented in the current STM.

In the future the STM will be used for new experiments. One of these experiments is to make atomic gold chains. For this experiment several gold atoms are randomly deposited on a gold (111) surface. These atoms will be moved to form a chain and then lifted from the surface. For this experiment the tip will not always be within a region of interest so an XY coarse stage is needed.

For another experiment several molecules are randomly deposited on a graphene surface. Through this graphene an electrical current will flow. And the tip will be brought close to the surface, just within reach of tunneling. For this experiment the tip will not always be within a region of interest so an XY coarse stage is needed. Also for this experiment a current through the sample is needed, which is not possible at the moment since the sample holder only has one electrical contact, which is used for the bias voltage.

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<sup>3</sup> Note that titanium becomes superconducting below 400 mK or lower depending on its properties. Superconductors are thermal insulators, but the *Ti* used to fabricate this STM becomes superconducting below 270 mK, which is not a concern for the STM in Leiden (Base-temperature  $\approx$  300 mK)



## 2. Piezoelectric motor

Piezo elements are often used for the movement of STM's and other (near) atomic resolution measuring tools such as AFM. Piezo elements are used for this purpose because of their capability to make small movements with high accuracy. The most commonly used material for these piezo elements is PZT. This material is UHV compatible, is not affected by high magnetic fields and can be used at low temperatures although the piezoelectric effect is reduced by the low temperatures [5].

### 2.1 Piezoelectric elements

Within PZT material, the orientation of the domains that are responsible for the piezoelectric effect is random. To be useful, the PZT material must be poled in a high electric field to orient the domains in one predominant direction. The material is poled in such a way that the material makes a shear motion under the influence of a high electric field, this is called shear mode piezos. The material and the piezoelectric effect are discussed in detail in appendix B. [5].

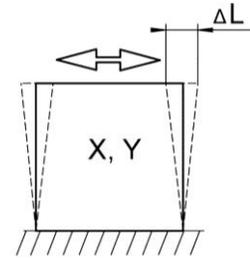


Figure 2.1: Simplified representation of a shear piezo element. The dotted lines represent the displacement when a voltage is applied. The voltage is applied over the bottom and top of the piezo [6].

Each piezo element that is used consists of several slabs of piezoelectric material. This is why these piezo elements are also called “piezo stacks”. Whenever a voltage is applied on these stacks, the stacks shear as shown in figure 2.1. The displacement of the shearing exerts a force on the object that is on top of the piezo stack. This force is in the range of several N and the displacement in range of a micron, but both will decrease significantly at low temperatures because the atomic structure of the PZT material becomes stiffer. Note that only shear mode piezos actually shear, the other piezos are referred to as length mode and lengthen when a voltage is applied. These length mode piezos are not used in this thesis [5] [6].

### 2.2 Slip-Stick motion

One piezo stack will only give a small displacement to the sample or tip. In the coarse stage, both XY and Z, a much bigger displacement is needed. That's why in coarse stage a movement technique can be used called “slip-stick motion”. This technique has a much bigger range but lower accuracy than a fine stage. The coarse stage should have an accuracy that is about 1/3 of the maximum dynamical fine Z stage. The accuracy of the coarse stage should be between 10-100nm [5].

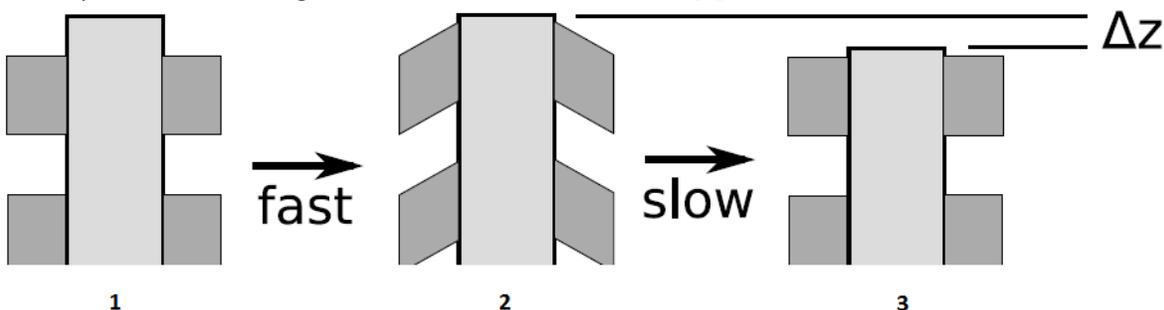


Figure 2.2: An illustration of the slip-stick motion. The four blocks on the sides represent the piezo stacks and the block in the middle represents the slider [5].

A representation of the slip-stick motion is shown in figure 2.2. The slider (shown as the block in the middle) is pressed between the four piezo stacks. The slip-stick motion consists of two phases: the fast and the slow phase. During the fast phase, suddenly a high voltage is applied on the piezo stacks. This needs to be done fast enough, in order that the inertial force of the slider will exceed the static friction between the slider and the piezo stacks. The piezo stacks will shear and the slider will stay in place. For the Z motor it is also important that the sliding phase should be short enough otherwise the slider can drop down due to gravity. Therefore the resonance frequency of the *entire* STM should be as high as possible (see chapter 4) [5].

Following the fast phase, is the slow phase. During the slow phase, the voltage is slowly decreased to 0V. This causes the piezo stacks to retract gradually, which in their turn move the slider along. In theory the slip-stick motion causes the slider to move the maximum displacement of the piezo stacks each time. This is not completely correct, because during the fast phase the slider slightly slides. This causes a smaller displacement per slip-stick motion, but still there will be a significant net movement of the slider [5].

## 2.3 Driving signal

The driving signal is the signal used for the shear movement of the piezo stacks. All the directions (X, Y and Z) have their own signal and are all connected in groups. This means that for example all the X piezo stacks are connected to the same signal.

### 2.3.1 The coarse stage

For the Z coarse stage (also known as the approach, which brings the tip in tunneling regime) the slip-stick motion is used. The slip-stick motion signal consists of a half parabola voltage pulse which is alternated by a slow voltage ramp to check for a tunneling current, both shown in figure 2.3a. If a tunneling current is measured, the tip is at the correct height for tunneling and the approach is finished [4].

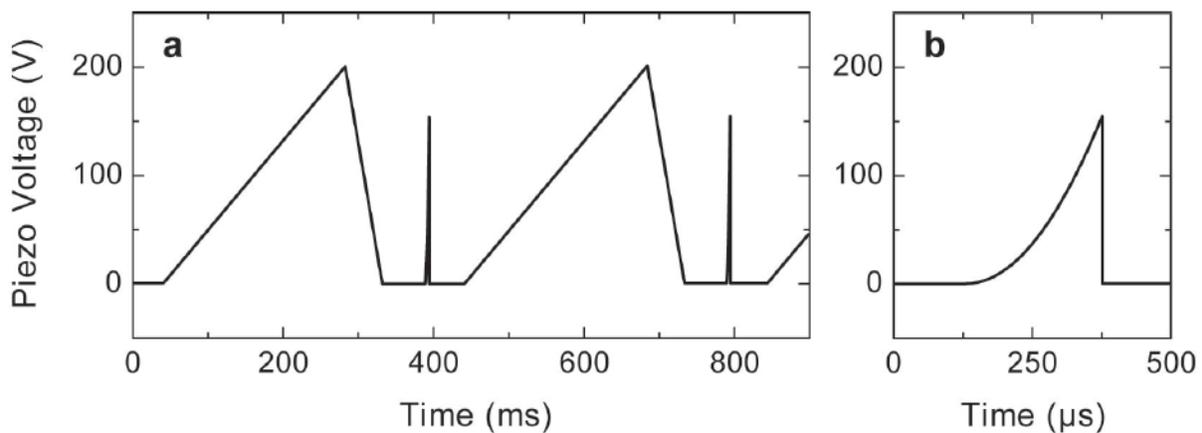


Figure 2.3: (a) The Z approach signal, consisting of a driving pulse (seen as the spike) and a slow voltage ramp. (b) The driving pulse, a half parabola with a sharp cutoff [4].

Also for the XY coarse stage the slip-stick motion will be used. Because in the XY there is no need to check for a tunneling current the only signal will be the driving signal as shown in figure 2.3b. This driving signal has a peak value of 160 V and duration of about 250  $\mu$ s [4].

### **2.3.2 The fine stage**

The fine stage is also known as the scanning stage. In this stage the sample moves in a zig-zag motion as seen in figure 1.1. During this zig-zag motion the X signal will be a saw tooth for scanning each line, while the Y signal will make a small step for each line that is scanned [4].

While this scanning takes place the tip will stay at the same height relative to the surface, it will 'follow' the surface. Whenever the distance between the sample surface and the tip changes, a change in the tunneling current will be measured. Thus to remain at the same distance from the surface the tunneling current should be constant. This is done by feedback. The feedback measures the tunneling current and will adjust the height of the tip by adjusting the voltage over the Z piezo. In this fashion the tip will stay always to the same height relative to the surface of the sample [4].



### 3. STM Design

The current STM has a solid design but is lacking on several points. The new design should maintain the solid points and improve on the weaker points. This means the combined Z coarse and fine stage (both located underneath the tip) will not change. To make sure the new design functions properly, several requirements will be discussed. These requirements help also to verify the design.

#### 3.1 Design requirements

The new design should comply with the following requirements to ensure its functionality:

1. The new STM could contain a combined coarse and fine XY stage, the XY coarse stage is used to move the sample to a different scanning position and the fine stage for scanning. This will keep the XY motor as small as possible.
2. There should be no rotation possible, both during scanning and loading the sample. If there would be any rotation this would disrupt measurements and possibly damage the STM. As  $\emptyset$  degree rotation is not possible in a design where X and Y directions are physically separated, we will set the maximum allowed rotation to  $4^\circ$  for the moment.
3. The displacement of the XY coarse stage should be at least a square of  $0.5 \times 0.5$  mm to ensure the XY coarse stage is useful.
4. The XY fine stage should at least scan an area of  $150 \times 150$  nm<sup>2</sup>. This to ensure there is enough area to image for most common STM measurements.
5. The resonance frequencies of the STM should be higher than 10 kHz, this to ensure the atomic resolution during scanning and a typical low temperature STM scanning speed of 500 ms/line, but also the move the X, Y and Z coarse motors as fast as possible.. In practice this means that the stiffness of the STM should be as high as possible.
6. The step size during the XY coarse stage should be at least 10-100 nm for most experiments.
7. There should be no crosstalk between the tunneling current and the signal of the piezo stacks. This crosstalk exists because the changing electric field inside the piezo stacks can influence the tunneling current. Since the tunneling current is used for feedback on the piezo stacks the measurement is very sensitive for crosstalk. The maximum crosstalk should be 500 pA.
8. The new STM should fit in the same housing as the old STM since the housing can't be changed. The housing has to fit into a bore of a superconducting magnet with a fixed size.
9. The STM will handle the same and new experiments. This means that the same materials and new materials with similar material properties should be used in the new STM.
10. Also should this STM allow new experiments, therefore while measuring a second current will flow through the sample. For this reason the sample holder will also have to be redesigned and the new STM design should allow more electrical connections throughout the body and a second connection on the sample holder.

After a few iterations of the design process, a promising design is created. The other designs will be discussed in appendix C. This design complies with all the requirements stated above. The design is based upon the Pan design by S.H. Pan *et al* [7]. The Pan design itself is used for the Z-motor, and will be

discussed appendix A since it will not be changed from the current design. The designs are drawn in AutoCAD Inventor™.

### 3.2 The principle of the design

The focus of this design is having the center of mass as close as possible to the plane of the movement, this will increase the stiffness. Particularly all motions which can be excited at the point where the sample is should be avoided by design. The basics of this design are shown in figure 3.1. If the piezo stacks (1) shear, the disc (2) will move to a direction of the shear motion. Connected to this disc is the sample holder (3), this is the place where the sample will be mounted. The disc also has a counterweight, which will alter the center of mass to the plane of the movement and minimize any vibrations.

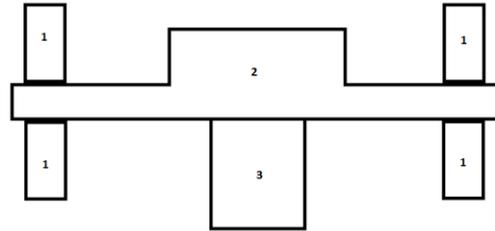


Figure 3.1: A simplified representation of the design. 1 is the piezo stack, 2 is the moving disc and 3 is the sample holder.

### 3.3 CAD drawings of the design

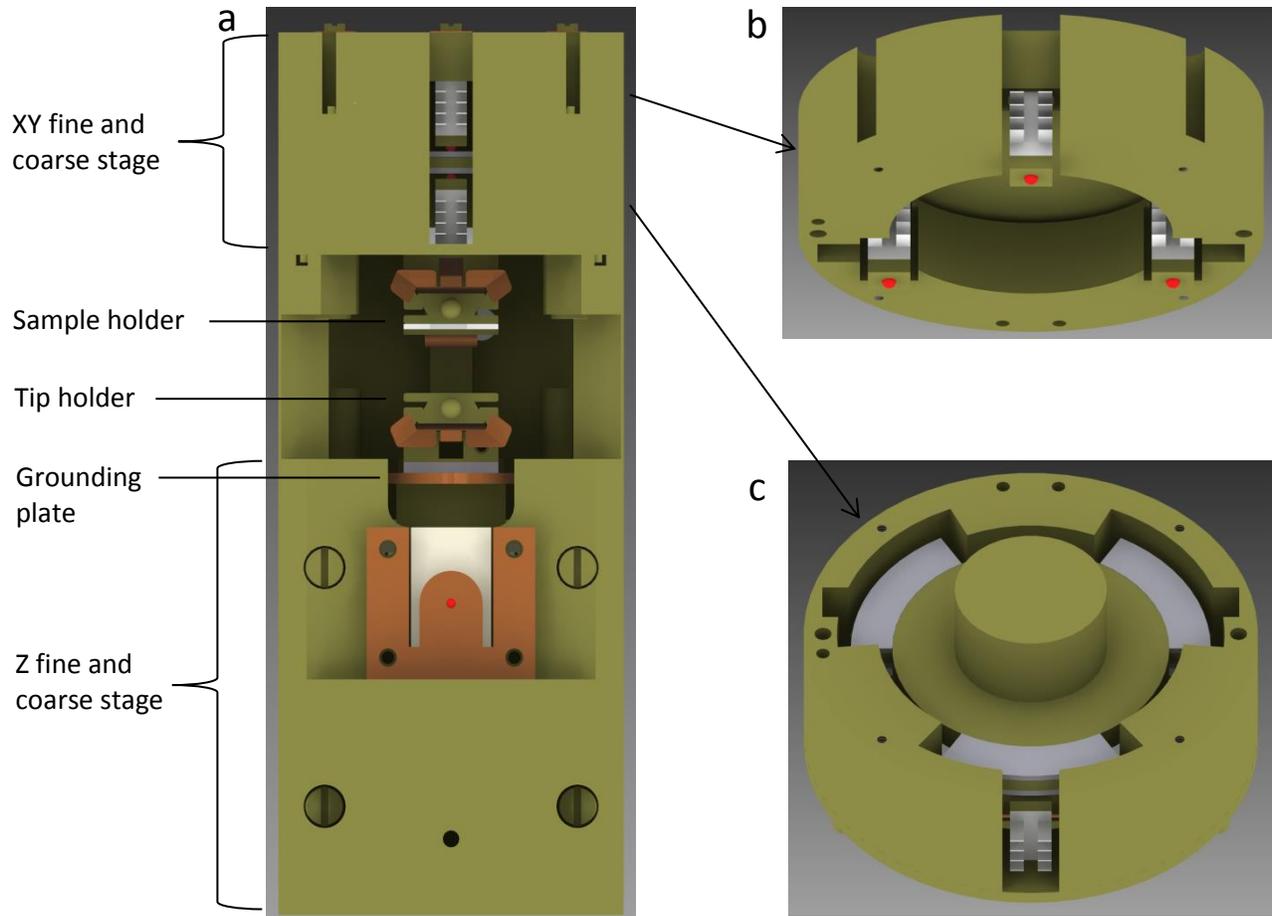


Figure 3.2: A schematic drawing of the design. The radius is 16.4 mm and the height is 81.3 mm. a) The whole STM. b) Top part of the XY fine and coarse stage. c) Bottom part of the XY fine and coarse stage. More about the grounding plate in paragraph 4.2.

The design is shown in figure 3.2. The design became more complex than stated in paragraph 3.2 to meet the requirements that are stated in paragraph 3.2. All the green parts are made of titanium, all the brown parts are made of 2% beryllium copper, the white parts are made of alumina (except the piezo stacks, they are made of PZT material) and the grey parts are made of optically polished alumina.

There are three upper and three bottom piezo stacks, these three stacks define a plane both on top and on the bottom of the disc so there will be no vibration because of an out of plane point. All these stacks are facing the same way because they have the same driving signal and need to move the same direction.

As shown in figure 3.2b, there is a red ruby ball on each stack. This ruby ball will have the minimal contact with the movable plate, and will decrease the friction with the movable disc. Glued on top of this plate, and between the plate and ruby ball, is a small alumina ( $Al_2O_3$ ) plate (displayed in grey). This plate will have a maximal roughness  $R_a$  of 100-50 nm. This will cause the friction to decrease even further, also the ruby balls are optically polished for this reason. The low friction is needed to make the slip during the slip-stick motion. If the surfaces are too rough the motion could stop and the accuracy will get much worse.

Figure 3.2c shows the lower half of the XY stages. In the middle is the moving disc, with several alumina plates glued on it. This disc can move in a circle with a radius of 1 mm (which will be the maximum displacement for the coarse stage). Note that the disc is not a full disc, it has several gaps on its outer ring. In these gaps there is a part of the body, this part will limit the rotation but not fully resist it. Nevertheless, such design where X and Y are not physically separated we cannot expect zero rotation (no rotation at all) during slip-stick.

In both the upper and lower part of the XY stages there are several holes. These holes are used for the electrical wiring. The role of the grounding plate that is shown in figure 3.2 is explained in paragraph 4.2.2.

On top of the upper piezo stacks is a disc which is pressed against the stacks by a spring. This gives the piezo stacks the normal force they need to keep the motor together and to have a reliable and constant preload. The spring also takes account for expansion or shrinkage when the temperature changes. This spring is shown in figure 3.3.

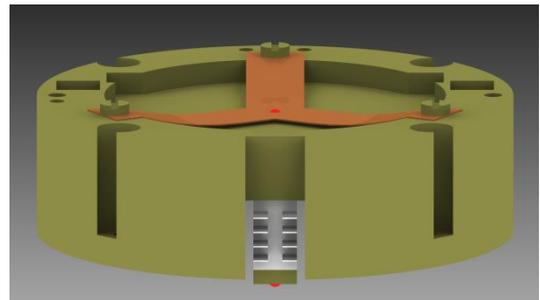


Figure 3.3: Schematic drawing of the new top part of the XY stage.

### 3.4 The new sample holder

The current sample holder is shown in figure 3.4. The sample holder itself is the upper part and will be replaced if the sample is replaced (the sample is fixed with epoxy or with mechanical clamps on the sample holder). The sample mount is the lower part, this part

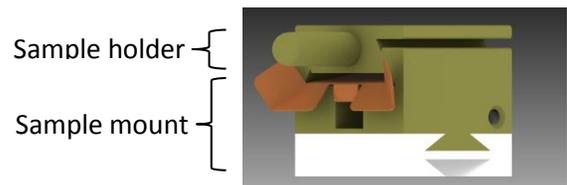


Figure 3.4: Schematic drawing of the current sample holder and mount. Sample is down facing the tip which points up in this STM (see Figure3.2).

is connected to the moving disc. Attached to the lower part is a spring, this spring will keep the sample holder fixed on its place.

On the sample mount the coax cable for the tunneling current is connected. If a tunneling current flows from the tip to the sample, the current will also flow through the sample holder and sample mount to the coax cable. At the end of this coax cable (at room temperature and outside the vacuum) there is an amplifier that makes the signal measurable and the feedback to control the Z fine stage.

Since there is a second current needed through the sample, the sample holder needs two contacts. The first step is isolating the sample from its holder (after all the metallic sample holder itself acts as a contact). This is done by gluing an isolating plate made of alumina on top of the sample holder, shown in figure 3.5 as the small white plate. This plate will have a hole on one side, which will be the first contact (because of the conducting sample holder). On the other side there is a small titanium strip on top of the alumina plate that will function as the second contact. This second contact will be made to the moving disc by a spring. Both contacts are separated by an alumina block seen in white above the sample mount.

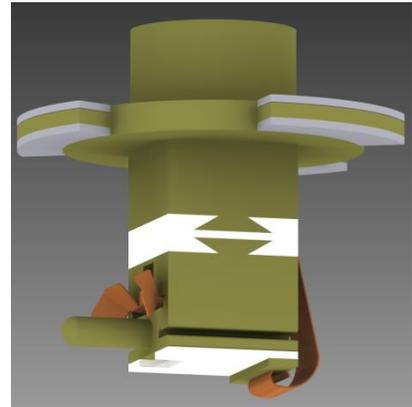


Figure 3.5: Schematic drawing of the new Sample holder and mount.

This new sample holder design keeps the current shape of the sample holder (especially the dove tail), this is essential because the dove tail is also used in various other places (for example the sample preparation chamber).

## 4. FEM calculations

FEM calculations give an analytic view of the model, with this view the model will be verified and checked if it meets the requirements. These calculations should be treated as estimation. The first and most important calculation is the resonance frequency analysis. These frequencies should be higher than of 10 kHz, this to have minimal vibrations during measurement and maintain an atomic level of accuracy, and to be able to drive the coarse approach motors last enough as mentioned previously.

The second calculation that is relevant for the design decisions is the electrodynamic calculation. This calculation is to verify that the piezo stacks do not interfere with the tunneling current signal. Minimal interference keeps noise and error levels low and also prevents potential tip crashes. For both calculations Comsol Multiphysics™ is used.

In both FEM calculations a model is drawn in AutoCAD Inventor™. This model is imported into Comsol Multiphysics™. In Comsol Multiphysics™ an applicable physics model is chosen and several conditions/constraints are applied to the model. After this the model will be meshed. Meshing is the process of dividing the model in small tetrahedral pieces, each of those pieces is called an element. By using a numerical calculation over all the created elements an approximate solution can be found.

## 4.1 Resonance frequency analysis

The model used for the calculation is shown in figure 4.1. The body and all the other parts that are inessential are not used in the model, because otherwise the model is too big and cannot be meshed.

The piezo stacks are shown in white, they are fixed by a fixed constrain on top side for the upper piezos and bottom side for the lower piezos. This means that that side cannot move. The ruby balls are shown in red. Between the ruby balls and the alumina plates a roller constrain is applied. This means that the ball and alumina plate are not connected but can move in the tangential direction.

The 'swinging' motion is the most harmful vibration mode, during this vibration the sample mount and holder swing back and forth. Other possible motions are for example vibration of the piezo stack electrodes. These motions are not responsible for the loss in accuracy, so they are neglected.

The calculated resonant frequencies of the swinging motion are 12.16, 12.24, 18.44 and 19.15 kHz. The visualization of the 12.16 kHz resonance frequency is shown in figure 4.2. The other swinging motions are similar to this.

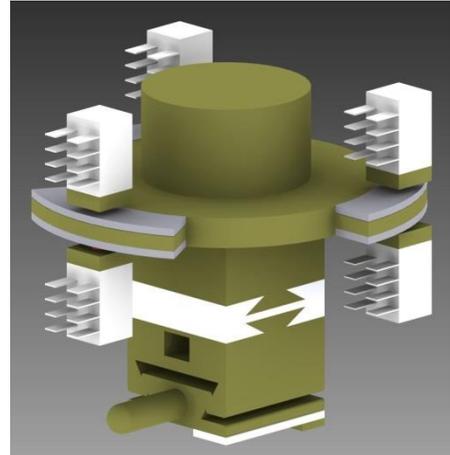


Figure 4.1: A schematic drawing of the resonance frequency analysis model. All the inessential parts are left out of the model.

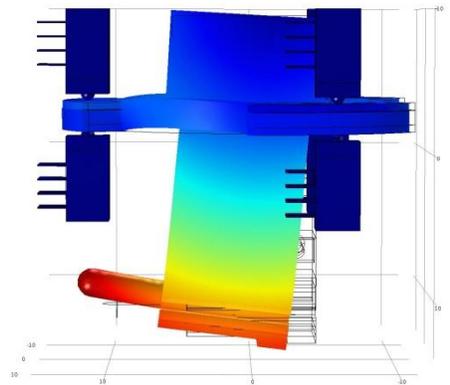


Figure 4.2: The calculated displacement of the 12.16 kHz resonance frequency. Dark blue means no displacement and dark red means the maximum displacement. The wire-frame blocks show the original position of the model.

## 4.2 Electrodynamic calculations

Since crosstalk is a major problem when measuring small signals (currents of nA or less), even with the current STM, both Z and XY stage are modelled. The electrodes of the piezo stacks are used as an electrical contact. On one side of the piezo electrodes the signal is applied and on the other a ground. All the piezo stacks are also electrically isolated on the top and bottom.

### 4.2.1 Z stage

The used model is shown in figure 4.3. The six piezo stacks are fixed around the slider and above the slider is the tip holder and mount.

As previously said the signal is applied on the piezo stacks. This signal creates an oscillating electric field. This field is the strongest inside the piezo stacks but also exists outside the piezo stacks stray field. This field creates an electric potential at the tip holder. The potential oscillates, together with the field. This induces a small current and is called capacitive coupling.

The tip holder and mount are both made of metal and therefore have a small capacitance. The capacitance can be approximated by a sphere [8]:

$$C = 4\pi\epsilon r \quad (2)$$

where:

$C$  = Capacitance (F)  
 $\epsilon$  = Dielectric constant ( $\text{Fm}^{-1}$ )  
 $r$  = Radius of the sphere (m)

The tip holder and mount are approximately a sphere with a radius of 5 mm and made of titanium ( $\epsilon = 8.858 \cdot 10^{-12} \text{ F/m}$ ). The approximated capacitance is 0.557 pF. Because of the electric potential the capacity builds up a static charge. This charge can be calculated by:

$$CV = Q \quad (3)$$

where:

$V$  = Potential (V)  
 $Q$  = Charge (C)

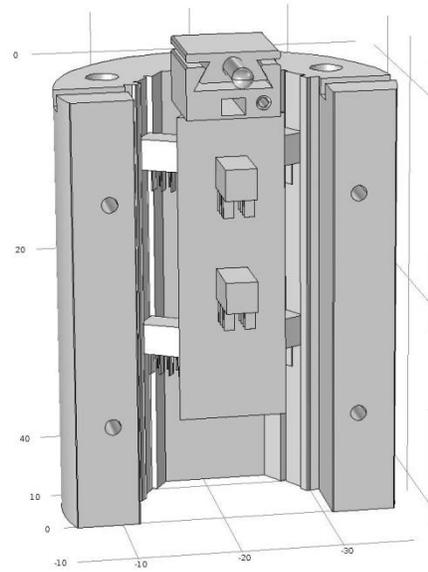


Figure 4.3: A schematic drawing of the used Z stage model for the electrodynamic calculation.

Since this charge is buildup over time a current passes through that will disrupt the measurement. This current is calculated by:

$$\frac{dQ}{dt} = I(t) \quad (4)$$

where:

$I$  = Current (A)

During the coarse approach motion, a signal with an amplitude of 100 V and frequency of 10 Hz is used. By applying the signal to the stacks in the simulation, the electric potential at the tip holder is maximal 35 V. By applying formula 3 and 4, the induced current is 0.196 nA. The measured CROSS-TALK current during the approach is  $0.2 \pm 0.05$  nA. This gives us some confidence that the model can be used for the other electrodynamic calculations.

During the coarse step the feedback is not active. This means the induced current during the approach is not a problem (only at the end of the approach when the tip is in tunneling regime), this is different from the scanning mode. During the scanning mode a signal with an amplitude of 10 V and a period of  $120 \mu\text{s}$  (8.3 kHz) is used. The maximum electric potential on the tip holder during this mode is calculated at 3.5 V, as shown below in figure 4.4. By applying formula 3 and 4 again, the induced current is 16 nA.

Since the measured signal during scanning mode is in this range, this induced current is a problem. Note that this scanning signal only applies to very rough surfaces of the sample. A normal scanning signal is slower and has a smaller amplitude. The 10 V peak to peak and  $120 \mu\text{s}$  are worst case scenario values. So during normal samples the induced current will be far lower.

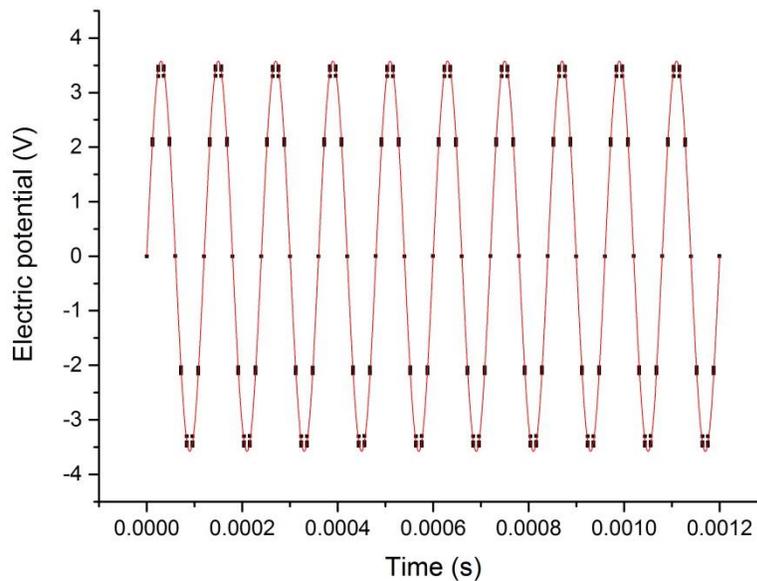


Figure 4.4: The calculated electric potential over time by the tip holder. The black points are the calculated points and the red line is a sinusoidal fit.

### 4.2.2 Z stage with grounding plate

The induced current can lead to crosstalk between the tunneling current and the piezo stacks. This happens because these two are linked by the feedback. This crosstalk can be prevented by shielding with a Faraday cage or any sort of metallic enclosure which is grounded because of space constrictions, one could use a grounding plate. Such a plate will be fixed between the tip holder and the piezo stacks and is grounded. Because this plate is grounded the electric field is a lot smaller on the other side of the plate, but for this to happen the plate needs to be bigger than the tip mount and holder.

The model with the grounding plate is shown in figure 4.5. The grounding plate is shown as a flat disc under the tip mount. The upper part of the disc is grounded. Between the mount and the grounding plate is an isolating alumina block. This block prevents that the grounding plate is getting short circuited by the bias voltage of the tip.

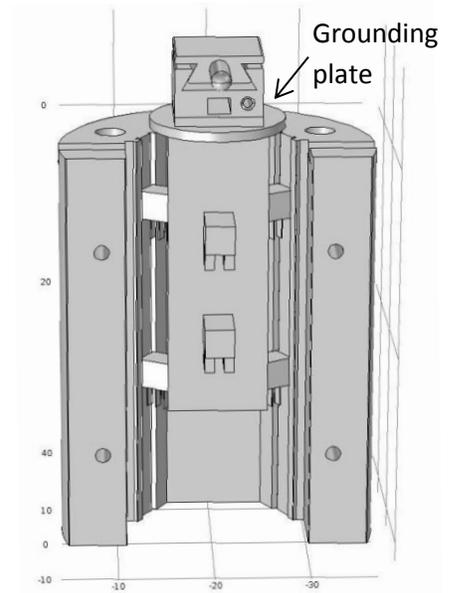


Figure 4.5: A schematic drawing of the used Z stage with grounding shield model for the electrodynamic calculation.

The calculated electric potential is shown in figure 4.6. The signal applied to the piezo stacks has an amplitude of 10 V, and a period of 120  $\mu$ s. As shown in the picture the maximum electric potential is 0.1 V. This potential induces a current of 0.46 nA. The current is, due to the grounding plate, 35 times lower.

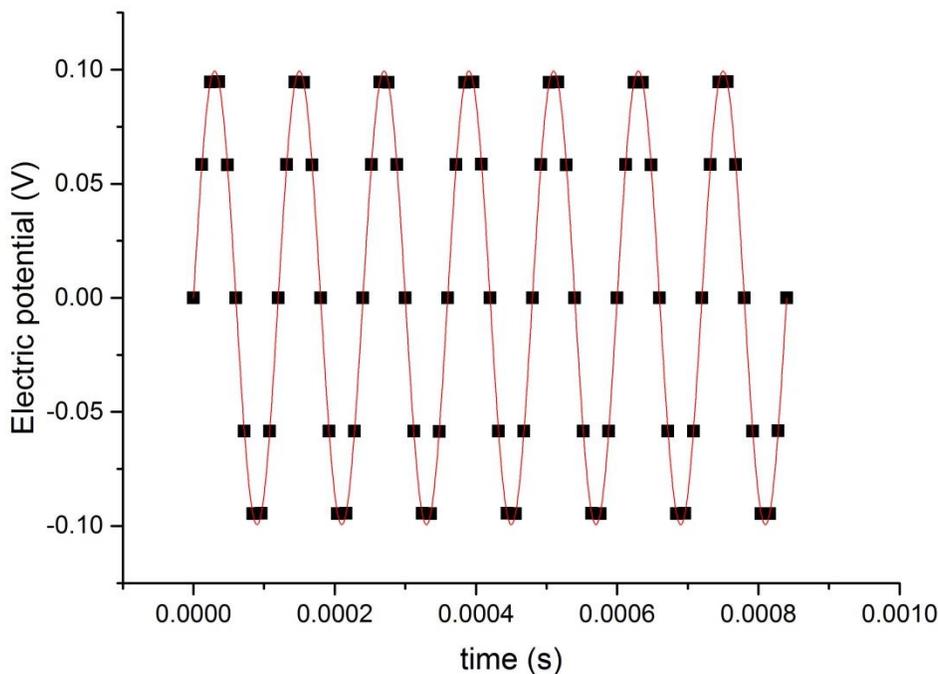


Figure 4.6: The calculated electric potential over time by the shielded tip holder. The black points are the calculated points and the red line is a sinusoidal fit.

### 4.2.3 XY stage

The XY stage model is shown in figure 4.7. The piezo stacks are located on top and underneath the moving disc. The signal that is applied to the piezo stacks has an amplitude of 200V and a frequency of 2 Hz.

The calculated electric potential is shown in figure 4.8. The maximum electric potential on the sample holder is 35 V. By applying formula 3 and 4, the induced current is 39 pA. This current will not cause any problems for the feedback or the measurable current, unless STM measurements are performed in this range which is less common (mostly in the nA range).

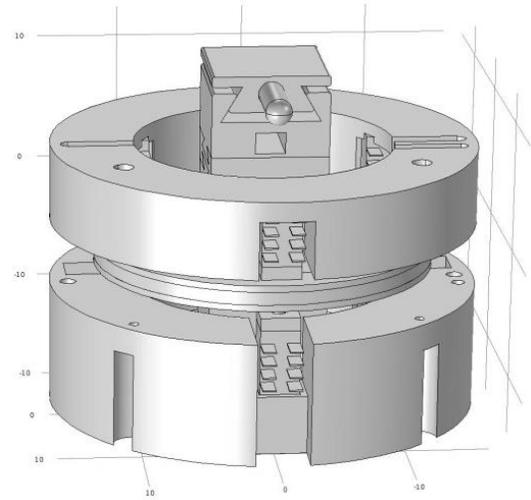


Figure 4.7: A schematic drawing of the used XY stage model for the electrodynamic calculation.

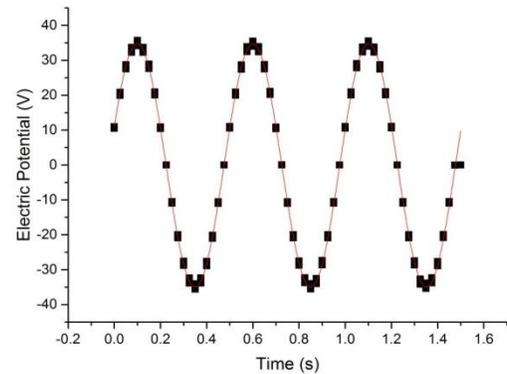


Figure 4.8: The calculated electric potential over time by the sample holder. The black points are the calculated points and the red line is a sinusoidal fit.

## 5. Conclusion

A new and promising STM design is made with a XY coarse stage. This design is based upon the Pan design by S.H. Pan *et al* [7]. In this design the XY coarse and fine stage are combined, just like the current Z stage. Also in this design the Z stage will remain the same. The materials used are alumina, beryllium copper, PZT, ruby and titanium. These materials can withstand low temperatures, high magnetic fields and UHV. These conditions are essential to the functioning of the STM. The STM is 32.8 mm wide and round, and 81.3 mm high. This means it will fit in the same housing as the old STM.

The XY coarse stage should be capable of moving in a radius of 1 mm, with a high accuracy. In this design we aim for a minimum step size of 10-100 nm, but testing at room temperature, low temperatures and UHV will have to be performed to verify that the actual numbers meet the expectations. This testing phase lies outside the scope of this project.

This accuracy is established through high stiffness and precise machining. Due to the stiffness the first resonant frequencies are calculated at 12.16 and 12.24 kHz. It is expected that the accuracy of the fine stage will not change since the force and the displacement of the piezo stacks do not change. The rotation is in this design not completely blocked, but is resisted after a certain point. After a small rotation further rotation is blocked and can be corrected by driving the sample to the center position.

Since crosstalk shielding is a point of improvement in the current STM, a model has been made. This model is validated by calculating the measured current during the Z approach (since it is not in the tunneling regime the tunneling current is zero). The calculated induced current is 0.196 nA this is in agreement with the measurement of  $0.2 \pm 0.05$  nA. The Z crosstalk while scanning has been calculated at 16 nA. This is higher than the tunneling current, and creates crosstalk. To counter this, a grounding plate was added to the model. This grounding plate reduced the crosstalk to 0.46 nA. The calculated crosstalk for the XY stage is neglectable.

New experiments will be done in the future with this STM. That's why a new sample holder is needed, which permits 2 currents through the sample. This sample holder has been designed with the same shape as the current sample holder, so it will fit in the sample mount.

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## Appendix A: Z motor by Pan Design

The design used for the Z motor is the Pan Design. It was developed in 1999 by S. H. Pan *et al* [7]. A drawing of this piezo motor is shown in figure A.1. It consists of a triangular slider with 2 piezo stacks on each of its sides. The slider can move in the vertical direction by doing a slip-stick motion.

This design is simple, effective and can operate with a high precision. The precision is based on the machining precision and the assembly. That's why it has to be machined very precisely and the stacks are glued in place, so they adapt to any errors of the machining.

The Pan design has proven itself to be reliable and stable for low temperature STM. The design has been digitalized and can be seen in figure A.2. Also visible in figure A.2b is a preloaded spring that takes account for temperature changes and the normal force on the slider. Also note that for the fine stage a scanning tube (a scanning tube is a tube with piezo elements that is used for the x, y, z fine stage) is used in the original Pan design, and in the current design both fine and course are combined by using the piezo stacks also for the fine Z stage. This is the so called Leiden design.

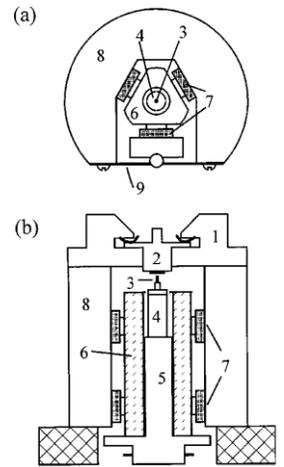


Figure A.1: Drawing of the Pan design.

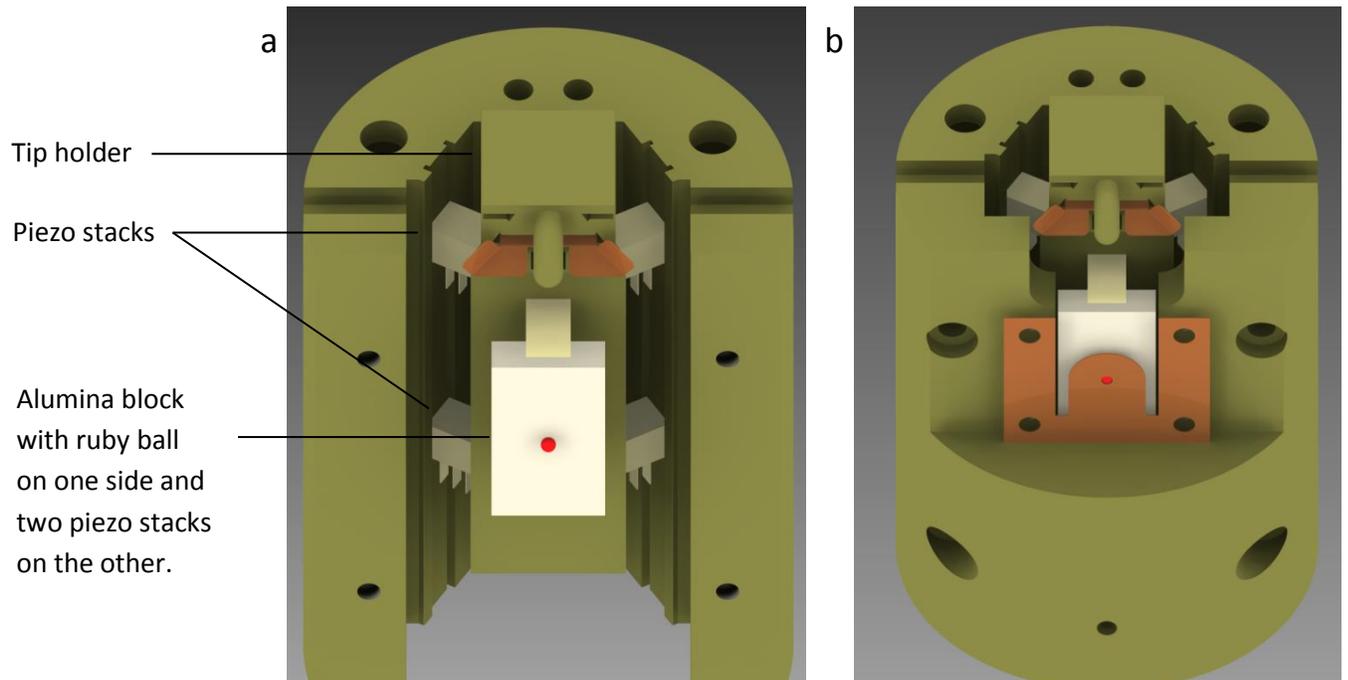


Figure A.2: The Z piezo motor can be seen. a) A cross section of the piezo motor. b) The piezo motor with the surrounding body. The spring can be seen which gives a normal force against the slider.

## Appendix B: Piezoelectric effect

In the piezoelectric crystal each cell of the crystal lattice spontaneously polarizes along one of a series of allowed directions. This spontaneous polarization disappears at the Curie temperature ( $T_c$ ), above which the crystal becomes paraelectric [5].

If the material is cooled through the Curie point in the presence of an external electric field, the dipoles tend to align in the allowed direction most nearly aligned with the field. Both the situation above and below the Curie temperature are shown in figure B.1a [5].

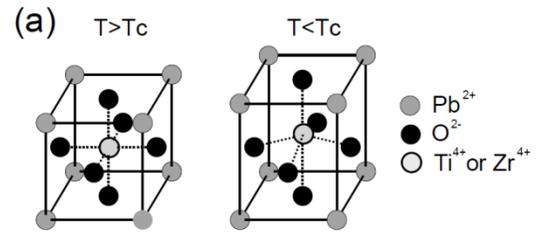


Figure B.1: a) Structure of PZT in cubic above  $T_c$  and tetragonal below [5].

The PZT material may be considered as a mass of crystallites, which are randomly oriented. Such material will be isotropic and will exhibit no macroscopic piezoelectric effect because of the random orientation. The ceramics are to become piezoelectric in any chosen direction by applying a strong electric field to it. It should be noted that not all the domains become exactly aligned. Some of the domains align only partially and some do not align at all. The number of domains that align depends upon the poling voltage, temperature and the time the voltage is held on the material. During poling the material permanently increases in dimension between the poling electrodes and decreases in dimensions parallel to the electrodes. When the field is removed, the dipoles remain locked in alignment, giving the ceramic material a remnant polarization and a permanent deformation (making it anisotropic), as well as making it permanently piezoelectric [5].

When an electric field is applied after poling, the piezo stacks shear (they can also lengthen but lengthen piezo stacks are not used in piezoelectric motors). The shearing motion is non-linear, which means as the piezo shears throughout its full range, it moves less per applied volt at the beginning of the shear than near the end. Also the piezo stacks have hysteresis behavior while shearing. Both the hysteresis and non-linear behavior are shown in figure B.2. The hysteresis effect becomes smaller at (far) lower temperatures [9].

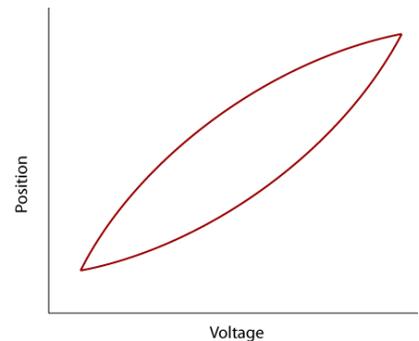


Figure B.2: Shearing motion of the piezo stack versus the applied voltage over the piezo stack.

The stacks used for this project typically have a loss of the piezoelectric coefficient of a factor of 5 from a temperature of 300 K to 4 K.

## Appendix C1: Design 1 ‘The wire design’

The first design that was considered is what we call the ‘wire’ design. This is also used in some low temperature STM’s in Alicante (ES) and Nijmegen (NL). The design is shown in figure C.1. The top piezo stack is responsible for the coarse stage. During the XY coarse stage this piezo stack will make a slip-stick movement and will move the middle disc to another position. The top piezo is connected to the body on the top.

In the middle of the piezo stack and the disc there is a hole, through this hole there runs a wire which is connected to the disc. Because the slip-stick motion needs a normal force, a spring is connected to the other side of the wire. This spring pulls the wire up, which on his turn delivers a normal force, also against gravity in this case.

Now for the fine XY stage a second piezo stack is needed which is connected to the disc. This piezo stack will make the scanning motion.

This design has several disadvantages. If the disc moves, the wire will be under an angle which may change the normal force. During slip-stick motion this will create an unbalance in the disc, which will give vibrations and uncontrollable movements. Also the wire limits the movement of the disc, because it only can move inside the hole. So at a certain displacement it will touch the walls and stop the movement. The wire itself will also allow unwanted vibrations that will decrease the accuracy. Finally, the wire can become a problem or get damaged during sample transfer with the wobble stick. For these reasons there has been decided that another design would be made.

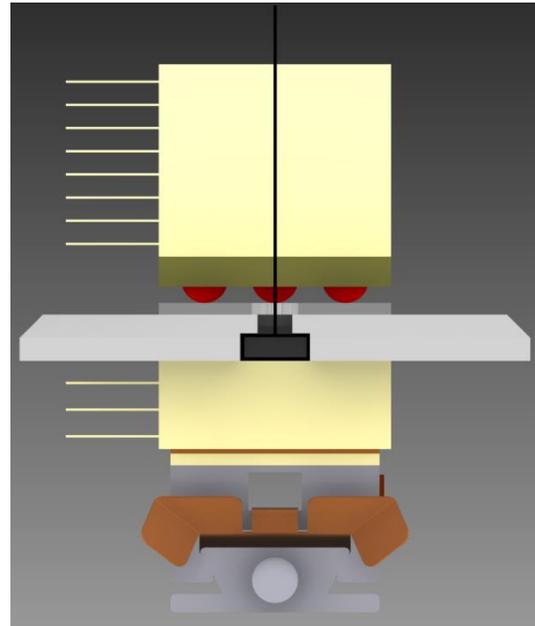


Figure C.1: A schematic drawing of the wire design. The black line represents the wire and the top piezo stack is connected at the top.

## Appendix C2: Design 2 ‘The bearing design’

The second design is based on the previous design, but pushes instead of pulling. The design is shown in figure C.2. The sample piezo stack and disc can be seen, both now without a hole.

The disc is being pushed against the piezo stack by leaf springs from the side. These leaf springs are preloaded by a screw, if the screw is tightened the preload will be higher. Between the leaf spring and the disc is small ruby ball. This ruby ball focusses the force on a single point, but since the disc will move in the horizontal plane the ball should be able to

rotate (to stay in the same position while moving). Since the ball should rotate there should be a bearing in the disc for the ruby ball. But bearings pose a problem, they have to be machined very precise and lubricated. Lubrication can be a source of problems in UHV and at low temperatures. Also, thermal shrinkage can cause problems to bearings. The design is interesting, very compact and simple but there is little experience with miniature bearing systems at very low temperatures.

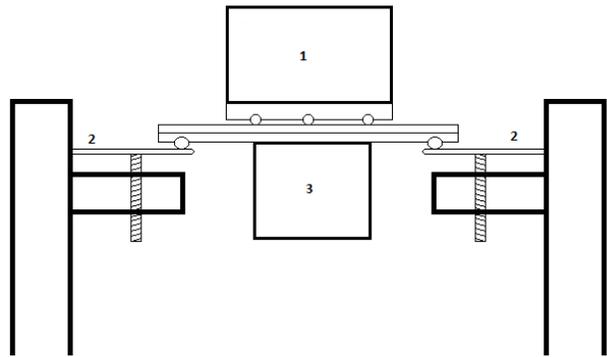


Figure C.2: A drawing of the second design. 1) Piezo stack connected to the body on the top. 2) Leaf spring that is being preloaded by a screw. 3) Sample holder and such.

### Appendix C3: Design 3 ‘The Greek temple design’

The third design is based on a design of H.J. Hug *et al* [10]. The design is shown in figure C.3. The sapphire plate is being pressed between piezo stacks. The bottom piezo stacks are connected to the body, and the top ones to a spring which gives preload for the slip-stick motion. If these piezo stacks shear the sapphire plate will move to the direction of the shear motion, connected to this plate is another top plate with the sample. This plate will also move [10].

In the original design the piezo stacks all have a different signal. This means that they can do next to the slip-stick motion also the walker motion. The walker motion is similar to the slip-stick motion but only during the fast phase the piezo stacks shear one at a time. Since this is not possible and the space is too limited, the design has been adapted for this STM [10].

The adapted design is shown in figure C.4. As shown the amount of piezo stacks is reduced from three to one. These stacks are bigger to compensate for the loss of force and the loss of displacement. Because of these bigger stacks the space between the two plates is bigger. Also note that the spring has another design than in the original design.

Because of the space between the two plates the center of mass is far lower than the plane of motion, the resonant frequencies are around 5 kHz. This frequency is too low and it can compromise the stability of the STM and its resolution. Achieving atomic resolution at normal scan speeds could be more difficult if not impossible. It would also be more sensitive to external mechanical interference. For this reason there has been decided that another design would be made.

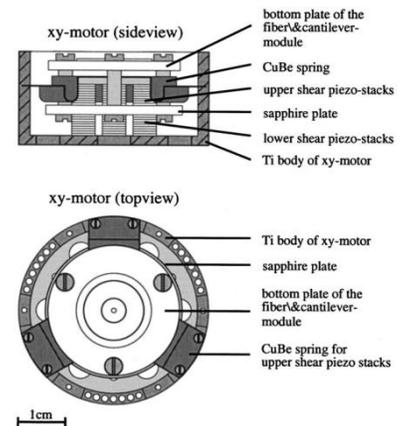


Figure C.3: Drawing of the design by H.J. Hug [10].

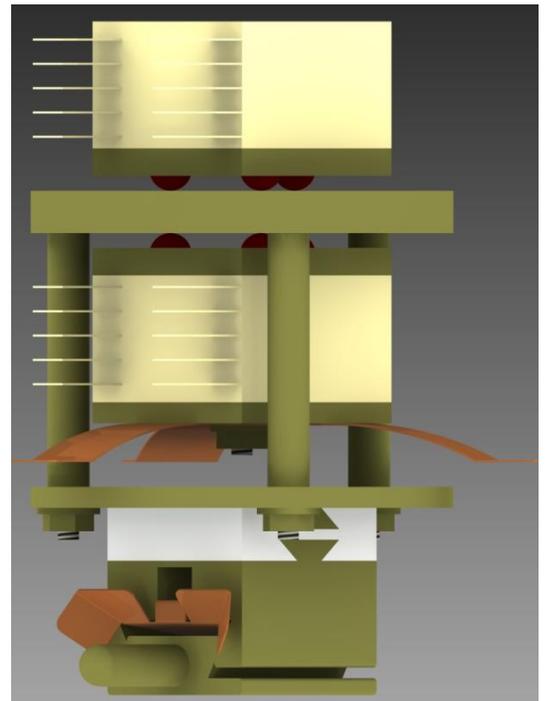


Figure C.4: A schematic drawing of the adapted design. The upper stack is connected to the body, and so is the spring which is connected to the lower stack.

## **Appendix D: The original assignment**

The student will be involved in designing a scanning tunneling microscope (STM) for use in extreme environments: ultra-high vacuum, extreme low temperatures (300mK) and high magnetic fields (10 T). The hosting group has already experience in this field. We have such a microscope in use but it needs to be upgraded with the extended option of XY coarse positioning. The student will be involved in the design together with a team of a researcher, a PhD student and mechanical technicians from the in-house Mechanical Department. The student will learn many aspects of scientific research and design of high-tech scientific equipment. He will also be involved in taking design decision together with the them. He will also be involved with the assembly of the new microscope and probably also with initial low-temperature tests – if time allows.