Towards High-Speed Scanning Tunneling Microscopy

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Chapter 4

Design of a high-speed STM with exchangeable scanning element

In this chapter we discuss the design of an STM setup and its UHV system, which will be used in the following chapters to test the performance of various high-speed scanning configurations. The design considerations are discussed first, followed by the motivation for our specific choice of geometry. After this, the technical details of the STM, sample holder and UHV system are discussed. The STM presented here enables a detailed study of the mechanical properties of various scanning elements, such as tube, stack or conical piezo element and MEMS actuators, at high imaging speeds.

4.1 Design considerations

For meaningful testing of the actuator geometries considered in this PhD thesis, both MEMS-based and piezo-element-based, a dedicated instrument is required in which high-speed imaging with atomic resolution is possible, both in air and under UHV conditions. To enable high-bandwidth measurements, we used high-speed electronics provided by Leiden Probe Microscopy [121]. Below, the mechanical design of the scanner is considered.

A dominant design specification is flexibility: the setup should allow the investigation of a variety of scanning elements: piezo-element geometries, such as tubes, stacks or conical piezo elements along with optional compensating piezo elements and the possible incorporation of a high-speed MEMS device. A further requirement is that the body of the STM scanner should allow for a quick exchange between different scanning elements. Piezo elements are usually glued on or clamped tightly in a holder; to allow for a fast switch, it should be possible to take this holder out of the scanner easily.

In order to enable fast scanning with a (heavy) scanning piezo element, the STM should have a high mechanical rigidity and high resonance frequencies. Also, the scanner should be constructed such that it can be used in a real-

istic experimental setting, where there is limited space available for a rigid structure and where the scanner often has to be moved (translated) while under UHV conditions for the purposes of sample cleaning and inspection with other imaging methods. This limits the maximum dimensions of the scanner to about 10 cm, which also limits the weight of the scanner body.
For scanning with a MEMS scanner, it is important that there is an optical path to the sample and the scanner, to allow a visual check of the alignment of the MEMS die and the sample.
The requirement of high rigidity and high resonance frequencies also applies to the sample holder. In addition, the sample holder has to be fit for various types of single crystal samples, with optional heating of the sample.
The STM setup will be placed in a UHV chamber to allow experimental studies on various surfaces. For this purpose, pressures below 1×10^{-9} mbar have to be reached routinely, which puts a constraint on the materials that can be used. However, in order to meet the earlier requirement of quick exchange between different scanning elements, the UHV system should be easy to open and provide sufficient access to the STM scanner body, after which it should be pumped and baked out in a relatively short time. To clean the sample, a sputter gun has to be included.

4.2 Scanner design

Various high-speed scanners have been developed in recent years. A flexure stage scanner, such as presented for AFM in [35], is a very rigid mechanical structure. A flexure stage scanner offers decoupled scanning directions and high resonance frequencies of the scanner as a whole. On the other hand, because of the complex geometry of this type of scanners, it is not possible to quickly exchange the scanning elements of the various directions without altering major points in the design of the scanner as a whole, and therefore a flexure stage would not be the optimal structure for our work. High-speed scanning has also been done with a very rigid scanner with a stack piezo-element [30]. Like the flexure stage, this scanner geometry does not allow for quick exchange of scanning elements. In addition, sample cleaning is not possible because there is no optical path to the sample and the scanner. This also inhibits a visual check of MEMS die and sample alignment.
One type of STM that meets the two requirements of mechanical stiffness and easy scanning-element exchange, is the Beetle-type STM, which can be designed to be very compact, with a small scan plate to hold the scanning

element. The Beetle type STM has first been introduced by Frohn [122], based on an earlier STM design by Besocke [123]. The Besocke-STM was designed to be a very stable (with resonance frequencies above the typical resonance frequencies of laboratory buildings) and easily operable microscope, and introduced the concept of carrier piezo-elements at the periphery of the scanner, with a central scanning piezo-element. The later design presented by Frohn (figure 4.1) introduced a new coarse-approach mechanism. In this STM, the scanner is supported by three tube piezo elements that serve as approach motors. These piezo elements are standing on a ring that is divided in three 120° parts. Each of these is slightly tilted and thus serves as a ramp for one of the three legs. By stick-slip motion[1], the piezo elements can “walk” over the ramps and in this way position the tip on the scanning piezo element towards or away from the sample. It has been shown by Pertaya et al. [124] that the lowest mechanical resonance frequency of a Beetle-type scanner can be increased from 300 Hz to as much as 20 kHz using stack piezo actuators for the approach mechanism. As we will see, it is possible to design a Beetle-type STM such, that the second requirement, ease of scanning-element exchange, is also met: it is possible to incorporate the central scanning element in a holder that can be easily exchanged without having to adjust anything besides the electrical connections.

4.2.1 The scanner body and approach mechanism

The Beetle-type STM that we have designed is shown in figure 4.2, standing on the sample holder. The height of the scanner body is 4 cm. The approach is performed by moving the three outer piezo stacks in a stick-slip motion over the ramps of the sample holder. The approach piezo elements are glued on one side to the scanner body. On the other side, part of a stainless steel ball is glued against the piezo stack to provide a well-defined “point” contact to the ramps. Stick-slip motion is performed by slowly ramping the voltage on the outer piezo elements, thereby moving the scanner body while the contact of the approach piezo to the ramps remains stationary. Then, the voltage is quickly changed to its original value, causing the point contact between piezo and ramp to “slip” to a new position. The scanner body remains still during this part of the motion. We used the commercially available piezo stacks P-

[1]Stick-slip motion means that two contacting surfaces are alternating between sticking to each other, during slow motion, and sliding over each other, during very fast motion. How this is used for the approach mechanism of the STM is explained in more detail in 4.2.1.

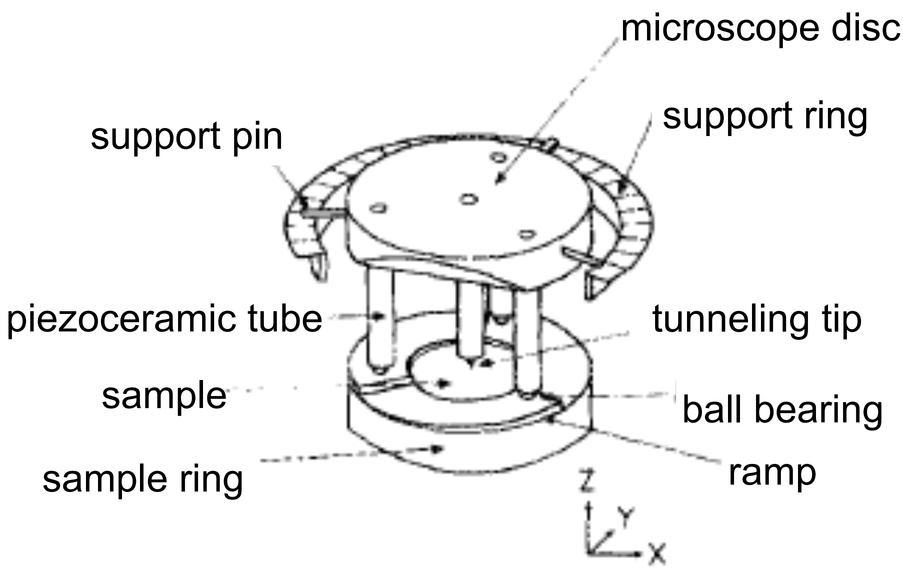

Figure 4.1: *First Beetle-type STM with stick-slip coarse approach mechanism. Reprinted with permission from J. Frohn, J.F. Wolf, K. Besocke and M. Teske, Review of Scientific Instruments 60, 1200-1201 (1989). Copyright 1989, American Institute of Physics.*

122.03 from Physik Instrumente [125] for this approach motor.
A known weakness of Beetle type STMs is the lack of reliability of this type of stick-slip approach motor, which can be even more dramatic when changing between atmospheric and UHV conditions and when wear accumulates on the ramps after a number of approach cycles. To test the reliability of our version of the approach mechanism before constructing the rest of the STM, and to determine the maximum ramp angle that this approach motor can climb on while carrying the weight of the scanner body, we have built a test setup with a mass identical to that of the scanner and with the same piezo elements. This test approach motor proved stable under atmospheric and HV pressures and at room temperature, up to a maximum ramp angle of 5.7°. In the STM design, the sample holder was machined with ramp angles of 2°, yielding a total approach range of 1.5 mm. In the complete STM setup the approach steps were later measured to be as small as 40 nm in the z-direction. In that geometry, an additional ring was placed around the ramps to make sure that the scanner body can never walk off one of them, which could lead to severe damage to the scanner and the sample. This ring is not shown in figure 4.2

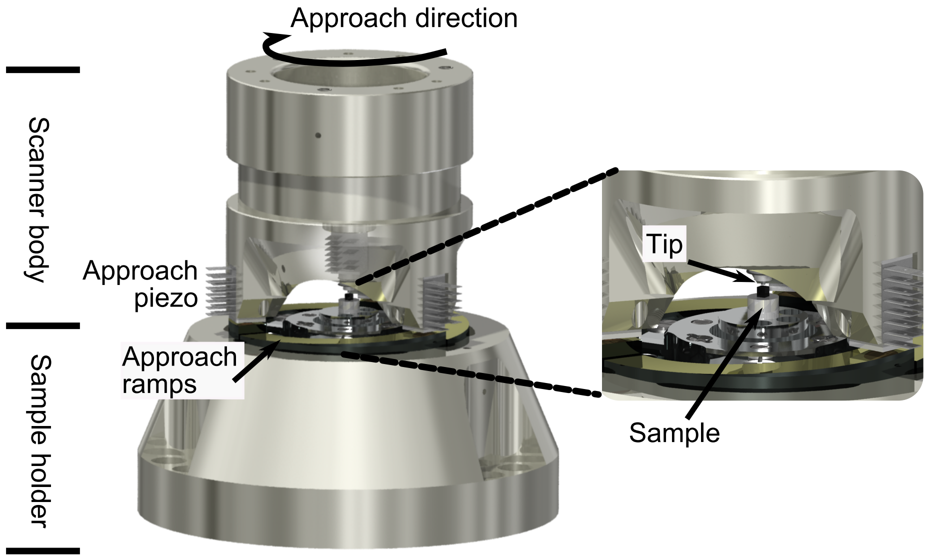

Figure 4.2: *Design of the scanner body (top part) standing on the sample holder (lower part). The three short legs of the scanner body are formed by stack piezo elements. These rest on three ramps in the ring surrounding the sample. Rotation of the scanner body by stick-slip motion of the piezo stacks over the ramps in the indicated direction makes the STM tip perform its coarse approach motion towards the sample surface. In the middle, a single stack piezo actuator is shown which performs the x,y,z scanning motion. The sample is mounted on an insulating plate in the centre of the sample holder. The height of the scanner body is 4 cm. The picture on the right shows a close-up view inside the scanner, displaying the tip and sample.*

to allow a better view on the ramps.

The central plate of the scanner holds the scanning element as shown in figure 4.3. This plate can be changed easily, allowing quick exchange and testing of various STM configurations. The middle part of the plate, where the piezo element is glued, is 1 mm thick. Improvement of the scanner resonance spectrum with a counter piezo element is expected to be most effective when a thin scan plate is used. For optimal performance with a single piezo element, a thicker central plate would be desirable. Although this is also possible in this versatile scanner design, we have not yet varied this important parameter.

4.2.2 Sample holder

The sample holder is located inside the contour, formed by the approach ramps of the Beetle scanner. For all tests reported in this thesis, we have used the ba-

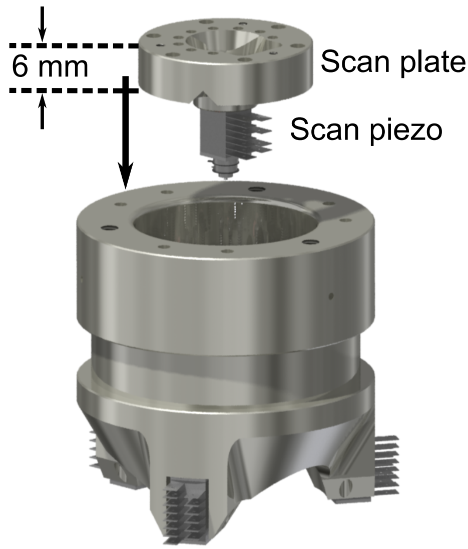

Figure 4.3: *Design of the scanner body, showing how easily a scan plate can be exchanged. Various scan plates can be mounted in the scanner, carrying different scanning piezo elements and/or MEMS devices. The central part of the scan plate, where the piezo element is mounted, is 1 mm thick.*

sic version of the holder, which allows quick exchange of samples. The sample holder design has been made such that it enables a straightforward upgrade to incorporate a heating filament and thermocouple connections. The middle part, carrying the sample, is mounted in a fashion similar to a kinematic mount, using three small extension springs and three ruby balls, 1.5 mm in diameter. This ensures a good mechanical stability of the sample holder. It is possible to place an I/V converter directly below the sample. This provides an opportunity to use a high-bandwidth (1 MHz) pre-amplifier at a distance of no more than 2 cm from the sample, thus limiting the capacitance at the input of the I/V converter to minimize the noise generated by the converter. This high-speed preamplifier has not been tested yet. A complete overview of the sample holder is shown in figure 4.4.

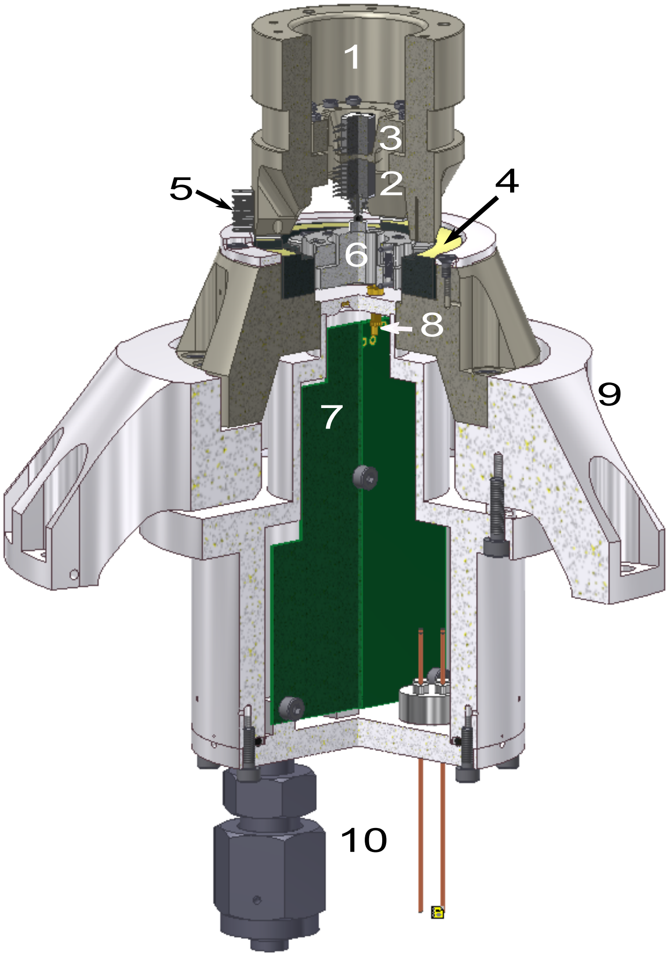

Figure 4.4: *Design of the fully equipped scanner and sampleholder, with mounted I/V converter. Shown are (1) the scanner body; (2) the (stack) scan piezo element; (3) the optional counter stack piezo element; (4) the approach ramps; (5) the approach piezo elements; (6) the sample holder; (7) the high-bandwidth pre-amplifier; (8) the first stage of the pre-amplifier; (9) the support of the sample holder and STM; (10) the external electrical connections to the preamplifier. The I/V converter is placed only 2 cm from the sample to minimize the parasitic input capacitance to the high-bandwidth (1MHz) I/V converter, caused by the input cable. The central part of the sample holder (6) can be replaced to include a heating filament and thermocouple wires.*

4.2.3 High-speed scan configurations

The first scanning configuration is a single stack piezo actuator from Physik Instrumente (type number P-123.01) with dimensions of 5 mm × 5 mm × 7.5 mm, an actuation range of 1 μm^3 and capacitances of 1.4 nF in both the x- and y-directions, and of 2.9 nF in the z-direction. This piezo element has a first axial resonance frequency, in the free-free configuration, of 155 kHz [125]. It is a compact stack piezo that combines shear piezoelectric plates for x- and y-motion with a thickness-mode piezo for z-actuation. This is the configuration shown in figures 4.2 and 4.3. In the second scanning configuration, the scanner houses the same piezo element, now combined with a compensating piezo element as is shown in figure 4.5. This is the same type of piezo element as the scanning piezo. The tolerance specified by the manufacturer on the actuation range is ±30%. In practice this means that the counterpiezo will not exactly cancel the force or torque introduced to the system by the scanning piezo. Still, calculations and experiments (discussed in more detail in 6.1) show that a better mechanical behaviour up to the resonance frequency of the piezo element is to be expected by the addition of a compensating z-direction piezo. The effects of the x- and y-counter piezo elements are less straightforward. These will be discussed in section 6.3.

In addition to the two scanning configurations mentioned above, it is also possible to include a custom-made conical piezo element (optionally with a conical counter-piezo element). This situation is shown in 4.6. Conical piezo elements have been shown to have beneficial properties for STM scanning [41], mainly due to the increased resonance frequency as compared to tube piezo elements (47 kHz with respect to 11 kHz). Conical piezo elements have not yet been used in STM experiments. Another option is to design a scan plate that can fit a conventional tube piezo element.

Finally, an important option is to replace the tip holder with a MEMS-scanner. This results in the hybrid scanning system, discussed in 2.3, combining the “best of two worlds”: a piezo stack providing fast x,y scanning motion and long-range z-scanning, combined with a short-range MEMS z-actuator performing the fast feedback motion necessary to follow rough surface features at high speed. The incorporation of a MEMS scanner on the scanning piezo element is shown in figure 3.20 on page 54.

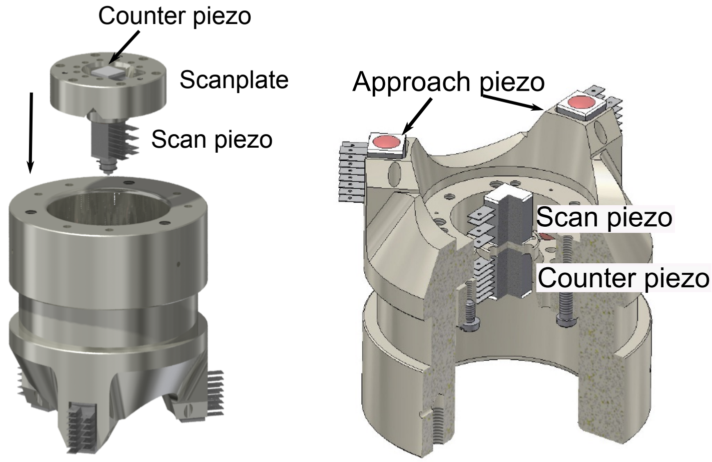

Figure 4.5: *Design of the scanner equipped with a scan plate carrying two stack piezo elements, one scanning element and one counter piezo element, compensating either the forces (in the x-, y- and z-directions) on the scanner or the torques (in the x- and y-directions). The left panel shows the scanner body with the scan plate unmounted above it; the right panel shows a cross-section of the scanner (upside down) showing the mounted scan plate with two stack piezo actuators.*

4.3 UHV system and eddy current damping

We have designed a basic UHV system that allows optimal testing of the different scan configurations, and permits the study of illustrative high-speed experiments. The UHV chamber is shown in figure 4.7. The top part can readily be lifted to allow good access to the scanner and the sample holder. This enables the user-friendly exchange of the scanner (and thus, the scanning element) and the sample holder. The connection between the top and bottom flanges can be sealed with a viton O-ring, if pressures above 1×10^{-7} mbar can be tolerated for quick testing, or with a copper gasket, if pressures below 1×10^{-7} mbar are required, for which the system has to be baked out. High vacuum conditions can be achieved quickly, using the 300 l/s turbo pump along with the ion getter pump. A quadrupole mass spectrometer (QMS) is included to monitor the residual gas composition. For sample cleaning, a sputter ion gun is installed, along with a “parking” structure for the scanner and a wobble stick, to remove the scanner from the sample holder. The complete setup is decoupled from building vibrations by pneumatic isolators (“air legs”). Below, all components of the UHV system are listed.

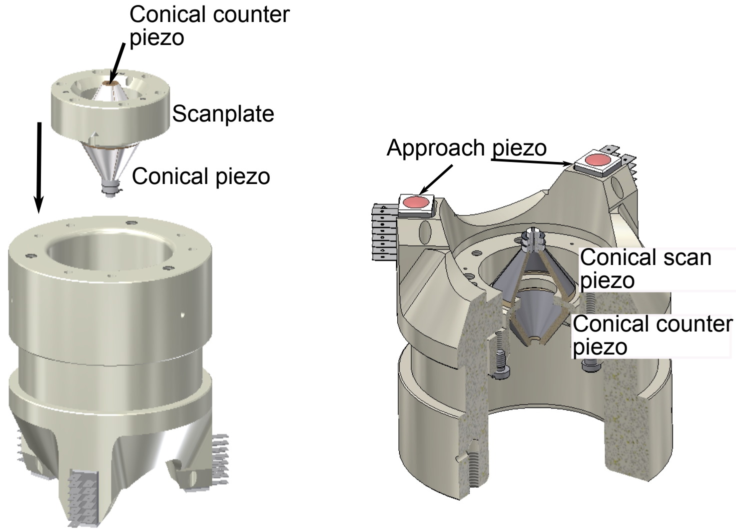

Figure 4.6: *Design of the scanner equipped with a scan plate carrying two conical piezo elements, one scanning piezo element and one counter piezo element, compensating either the forces (in the x-, y- and z-directions) on the scanner or the torques (in the x- and y-directions). The left panel shows the scanner body with the scan plate unmounted above it; the right panel shows a cross-section of the scanner (upside down) showing the mounted scan plate with two conical piezo actuators.*

- Ultrahigh vacuum chamber: in-house design, production at Vernooy [126].
- Pneumatic vibration isolators, 28 inch, Newport [127].
- Turbo-V301 pump, Varian (now Agilent) [128].
- Sh-110 dry scroll pump 5.3 m^3/hr, Varian (now Agilent) [128].
- Vacion plus 75 starcell pump, Varian (now Agilent) [128].
- UHV-24 ion gauge, Varian (now Agilent) [128].
- QMG 220 M1, mass spectrometer, Pfeiffer Vacuum [129].
- UHV gate valve 10840-CE44, VAT [130].
- Electrical feedthrough connectors: 2 floating BNC connectors, 2 thermocouple connectors, 2 10-pin connectors and 1 20-pin connector, Hositrad [131]

- Ion source IS 40C1; custom insertion length 310 mm, Prevac [132].
- Wobble stick ZWS 150PG, VG Scienta [133]

The assembly of the scanner, which is resting on the sample holder, which, in turn, is mounted on a spring-suspension system with eddy current damping, is shown in figure 4.8. The combination of a spring-suspension system and eddy current damping effectively reduces the most harmful vibrations originating from the outside world (building vibrations and acoustic noise). For the spring suspension, four springs with a free length of 76 mm, an outer diameter of 12.7 mm and a spring constant of 0.11 N/mm (by Lee Spring, type LE 041E09S [134]) were used. The eddy current damping was done with 24 magnets of 14×6 mm (type GSS18) by Goudsmit [135] with copper plates in between. The connectors of the scanner to the outside world are easy to decouple, so the scanner can be taken out of the UHV system quickly in order to change the scanning element without loss of time. To achieve this, we have made an intermediate connector with two 9-pins sub-d connectors and two BNC-connectors from Accu-Glass [136]. On one side, this connector leads to the scanner. On the other side, this connector leads to the (fixed) connections at the feedthrough flange.

4.4 Summary

A Beetle-type STM scanner has been developed that allows for quick exchange of the scanning element and provides the possibility to incorporate various scanning configurations, including tube, conical or stack piezo elements with optional counterbalancing piezo elements and the incorporation of a MEMS STM actuator. This STM scanner is placed in a UHV system which allows for quick testing of the scanner under HV conditions and for experiments under UHV conditions.

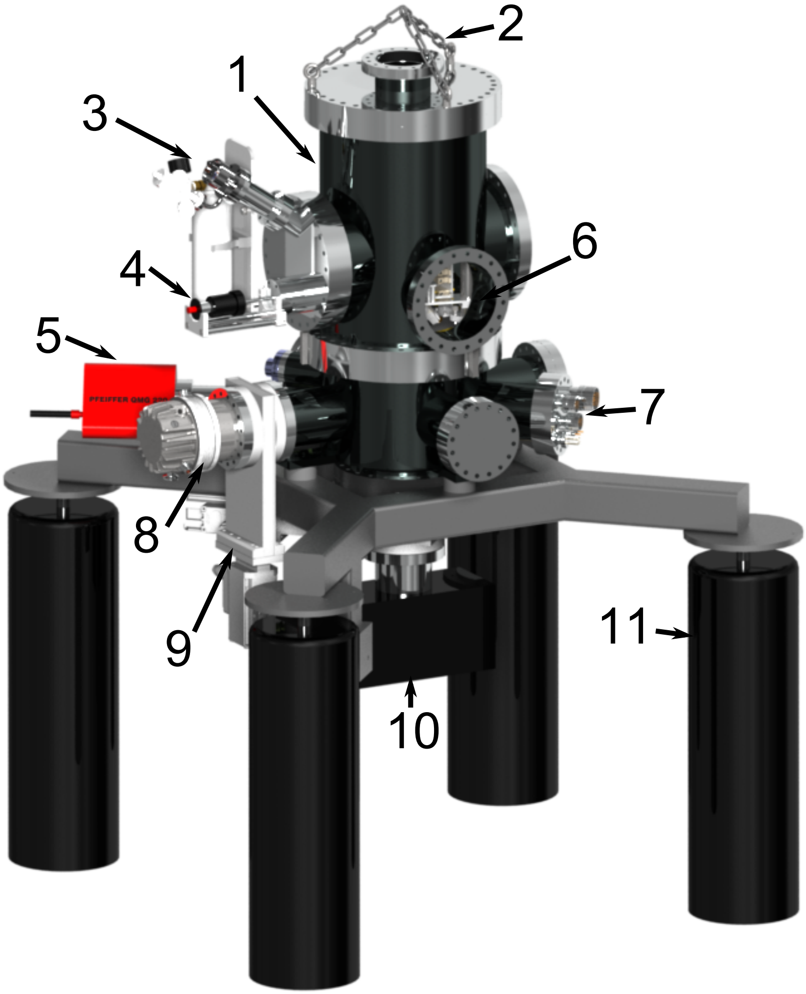

Figure 4.7: *The UHV chamber designed for high-speed STM testing. The most important components are (1) the top part, which can be lifted via a crane connected to (2) to allow access to the scanner; (3) a sputter gun; (4) a wobble stick to manipulate the scanner; (5) a quadrupole mass spectrometer for gas analysis; (6) view ports; (7) a feedthrough flange for electrical connections; (8) a turbopump; (9) a gate valve to separate the chamber and the turbopump; (10) an ion getter pump and (11) pneumatic isolators for vibration isolation.*

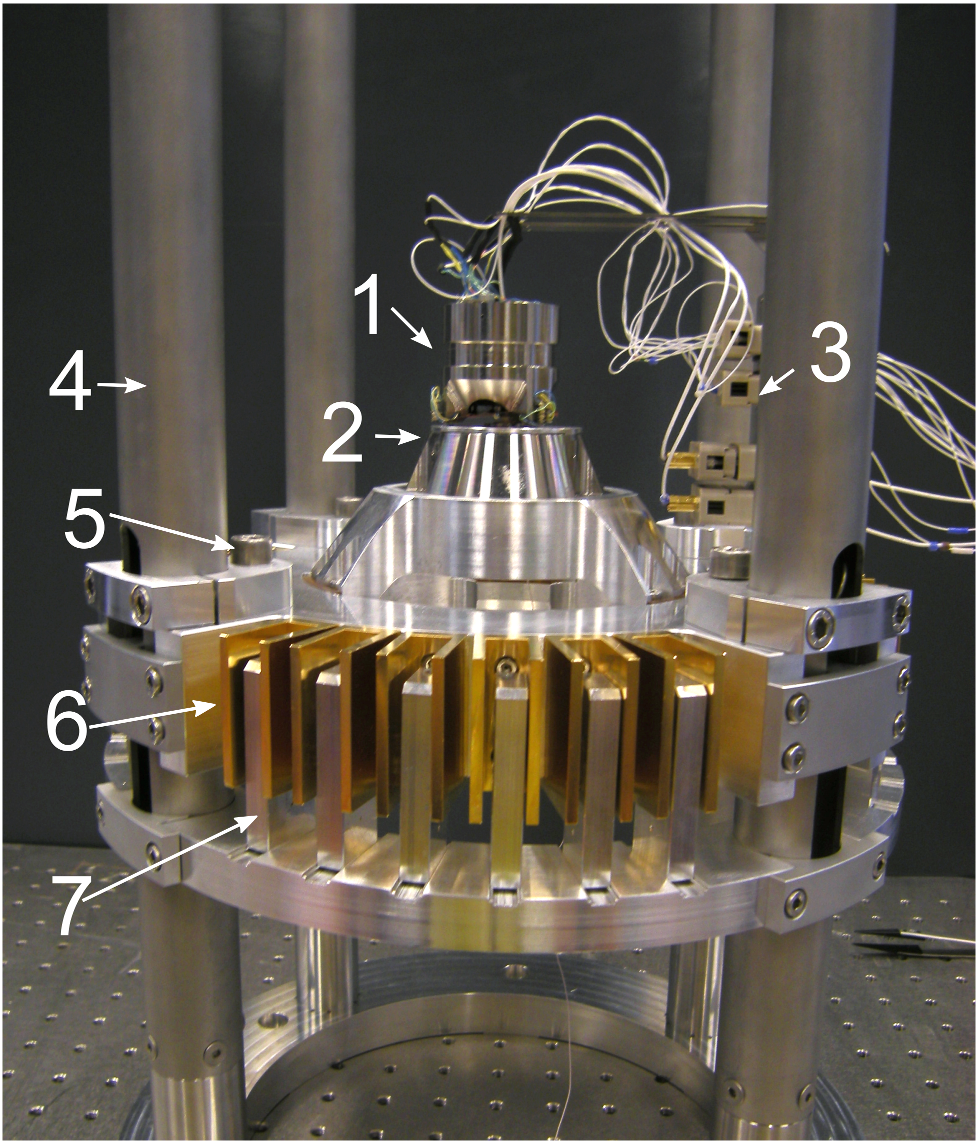

Figure 4.8: *Photograph of the scanner body, standing on the sample holder, which is mounted on the eddy current damping system. Indicated are (1) scanner body, (2) sample holder, (3) intermediate connector plate, (4) casing of spring suspension, (5) fixation point of spring suspension, (6) copper plate and (7) magnet of the eddy current damping system.*