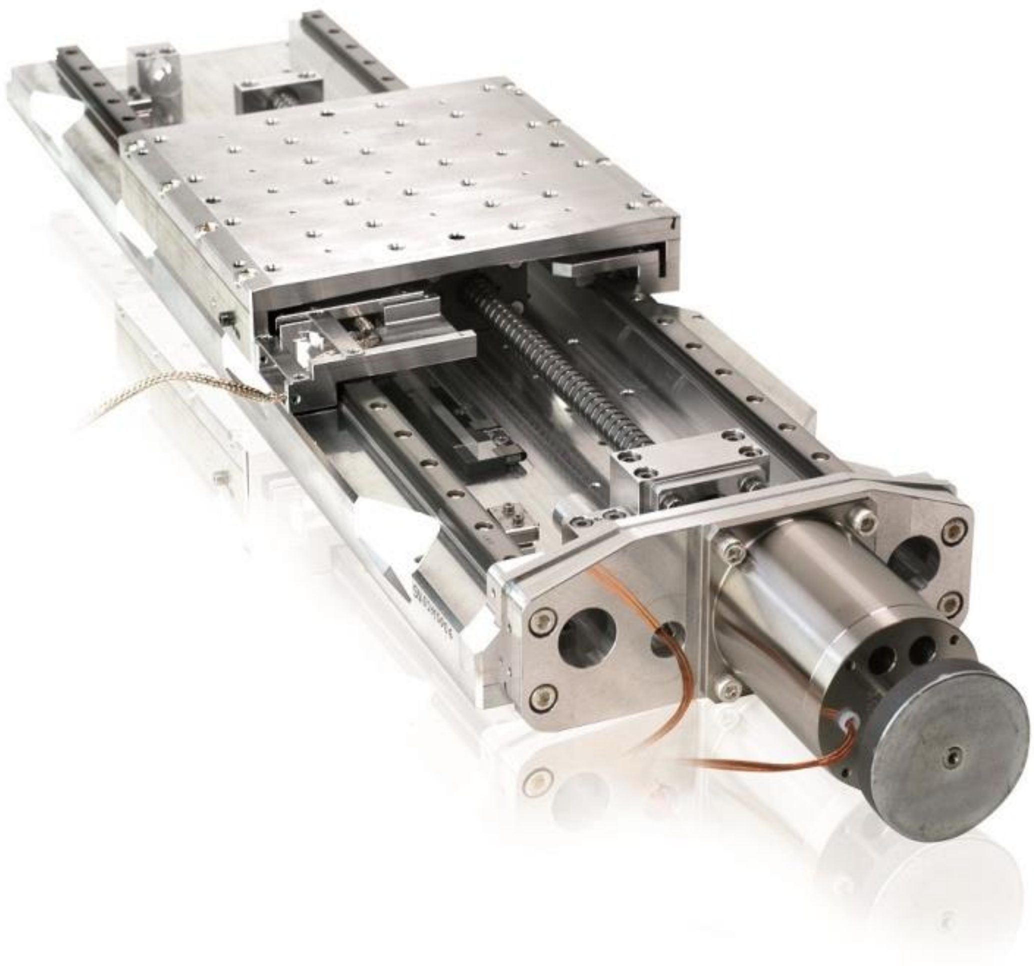
Motion Control and Precision Positioning in Vacuum Environments



1 Introduction

Vacuum applications are of growing importance due to technologies that can only be applied in vacuum or cryogenic environments. Scientific research as well as industry requires different vacuum levels depending on the processes. In optics technologies, lenses are coated in vacuum chambers; fiber and laser optics as well as sensitive detectors are manufactured in a vacuum. Throughout the worldwide research and development field, vacuum environments are used, from small epitaxy processes up to the large beamline facilities. Ultrahigh vacuum and very clean conditions are utilized in the semiconductor industry. All of these and many other applications often require reliable motion control in a vacuum, either for sample positioning and handling or for optics and accessories alignment.

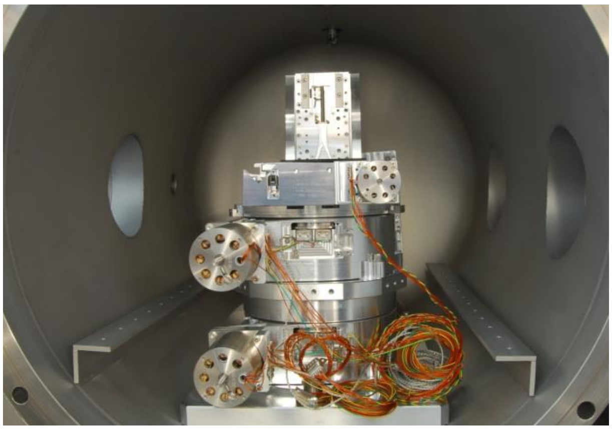


Fig. 1 Motion control in a vacuum chamber

To specify the required vacuum level, it is important to analyze the demands of the application. But additionally to the final pressure, the outgassing rate or the partial pressure of specific residual components are important. Hydrocarbons (HCs) for example, may be introduced into the vacuum chambers unintentionally because the wrong grease or plastic components were used. HCs are fragmented by strong UV light or X-rays and therefore, they are especially critical in laser applications in the UV range and in beamline applications. HC fragments deposited on optics surfaces pollute or even damage the in-vacuum optics or the test sample.

Overall, motorized positioners with low outgassing are needed. Further, the residual gas must contain very little or no HCs and no metals with high vapor pressure such as zinc, lead, or cadmium. In order to provide good products, a lot of effort has to be made. In the end, the materials and handling processes chosen are the most important requirements for designing a suitable vacuum stage.

The aim of PI is to develop and manufacture products for in-vacuum motion control. The products offered by PI range from atmospheric pressure to 10^{-9} hPa. In some cases 10^{-10} hPa can be reached. This paper outlines how PI achieves vacuum suitability for its products.

2 Definitions: Vacuum and Outgassing

Vacuum is defined {DIN 28400} as pressure lower than normal (atmospherical) air pressure. In this paper, hectopascal {hPa} is used as the unit of air pressure. Other commonly used units in physics are millibar {mbar} and Torr {Torr}.

Vacuum class	Abbreviation	Pressure range
Low vacuum	FV	<1 hPa to 10^{-3} hPa
High vacuum	HV	$<10^{-3}$ hPa to 10^{-7} hPa
Ultrahigh vacuum	UHV	$<10^{-7}$ hPa to 10^{-12} hPa
Extreme ultrahigh	XHV	$<10^{-12}$ hPa

Outgassing is the detachment of volatile molecules which are absorbed or adsorbed on the surface or in the volume of a material. Because the rate of outgassing defines the pressure in the system (together with the capacity of the vacuum pump), outgassing prohibits fast achievement of low pressure values. In addition, the outgassing compounds may deposit on surfaces of optical elements or other sensitive devices and may obscure or damage them.

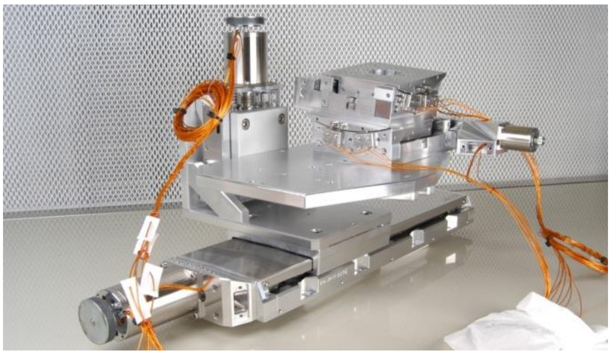


Fig. 2 Four axis system for ultrahigh vacuum application

3 Design and Manufacturing

Because outgassing is a challenge for creating and maintaining clean high-vacuum environments, the right choice of materials and treatments is compulsory in the design and production of vacuum systems. To achieve a high vacuum (HV) or an ultrahigh vacuum (UHV) positioning system, three main subjects must be taken into account.

3.1 Material selection

Standard electrical and electronic equipment such as motors, scaling systems, connectors or limit switches contain components that are either not suitable for vacuum applications or only suitable to a limited extent. Cables are usually shielded with PVC insulations, motors are lubricated with grease or oil with high vapor pressure containing hydrocarbons, and electronic parts are embedded in plastics with high outgassing rates. Avoiding outgassing from these components is a big step towards a clean vacuum.

Replacing PVC cables with PTFE or polyimide-shielded braids is technically simple but expensive. Polyimide in particular, has the necessary cleanliness for use in a vacuum, but it absorbs a lot of water molecules, which increases the pump-down period drastically. Therefore, only the number of braids necessary for operation of the positioning system should be used. The braids should be as short as possible, and ideally, the vacuum chamber is also designed for short cables.

Good vacuum motors have a number of holes for venting, are equipped with polyimide-shielded motor coils and ideally, have a temperature sensor implemented in the motor. Temperature control is important for two reasons: Firstly, the motor should be operated at a point below excessive heat generation which means that slow driving is recommended. Secondly, a temperature-controlled bake-out process by applying current to the motor must be performed at least for UHV systems. Therefore, all components for UHV stages must be able to sustain heat-up to a certain temperature. Typically, PI sets this temperature to 120 °C for stages with, and to 150 °C for stages without scaling system. Due to the huge number of windings of the motor coils, the amount of polyimide is very high and therefore, a large amount of adsorbed water must be baked out. Specially designed two-phase stepper motors are implemented in the UHV products as shown in the image below.

Standard connectors and limit switches cannot be used in a vacuum due to their high outgassing plastic components. They are supplemented by components made of low outgassing plastics (for HV) or ceramics, PEEK and metal (for UHV), as shown in the image below. The pins of the connectors and the contacts of the switches are not soldered, but either crimped or laser welded.

Fig. 3 Typical motors for UHV applications

The selection of materials for the chassis of the positioner is limited. For example, copper-zinc alloys should not be used in vacuum systems. Such materials are replaced by bronze if possible. Other standard plastic parts are substituted by PEEK, ceramics or metal components for UHV products.

Fig. 4 Example of small linear vacuum stage with UHV limit switches

3.2 Careful design

Substitution of standard materials by **vacuum-compatible materials** as described above, is a strict requirement of vacuum stage design. Another requirement is the **reduction and minimization of the surface** of the positioner. The surface of the uncoated body is not sand-blasted for vacuum stages. Covers for protection against contamination are usually not required for vacuum stages. Protective shields for limit switch electronics are not necessary in the case of mechanical limit switches. The title page image and the image below show two examples of stages without protective shields.

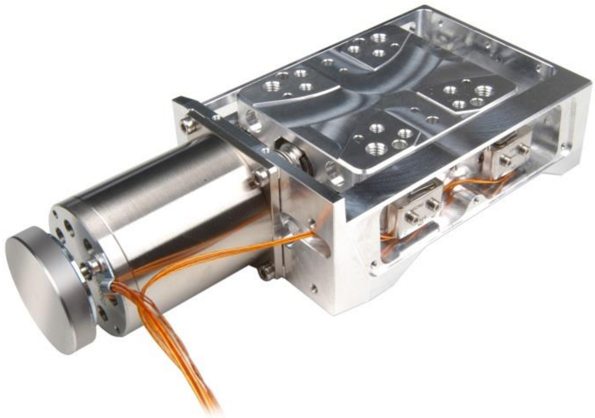


Fig. 5 PLS-85 UHV stage

The third and very important requirement in vacuum stage design is the prevention of **virtual leaks**. A virtual leak is a trapped volume connected to the vacuum side of a chamber. The gas in this trapped volume cannot be pumped out easily due to only narrow paths connecting to the vacuum chamber. This results in slow outgassing and appears to be a leak in the vacuum system. Poor design is the major cause of virtual leaks, not only for positioning stages, but for vacuum chambers and vacuum equipment in general.

Trapped volumes are usually caused by unvented or poorly vented blind tapped holes. These are either at the tip of a screw or under the rim of the screw head. Furthermore, holes that are covered either when mounting the positioner on a base plate or fixing a sample on the positioner, often cause virtual leaks.

In the case of virtual leaks caused by screws, the use of vented screws is recommended. Vented screws have a hole down the length of the screw to avoid trapped volumes, see image below. In this way, the trapped volume can be vented. Furthermore, the head of the screw has a groove to ensure venting of the cavity under the screw head. If the hole is covered by the positioning unit, which then causes a virtual leak, it must have either a perforation or an air vent groove.

Fig. 6 Examples of silver-plated vacuum screws

3.3 Cleaning, assembling and packing

Before a vacuum positioner is assembled, all pure metal parts undergo a cleaning process in an ultrasonic bath. Electrical and electronic units are wipe-cleaned. Standard lubricated components such as bearings and guides are degreased, cleaned and lubricated with special vacuum grease. Ultrasonic-cleaned components are dried in a climate chamber.

Assembling of a stage is done in a cleanroom or in a laminar flow system. After assembling, the stage must pass a performance test in clean environment. Vacuum tests are performed for each type of stage and when vacuum-critical changes are made to the product. Vacuum tests can also be performed on customer request. Details of such tests are discussed in the next chapters.

After assembling, the system is packed in vacuum-sealed bags protected against dirt, air, and humidity: First, the stage undergoes a baking process in a climate chamber. After packing and sealing in an inner vacuum bag, the stage is then put into a second, outer vacuum bag which is then vacuum sealed completely.

4 Equipment for Quality Control

PI miCos has two vacuum chambers with different volumes and facilities for bake-out and mass spectrometry for in-house vacuum tests.

4.1 Small vacuum chamber

For testing single components or for testing small stages, a chamber is available with a volume of approximately 10 l. The small vacuum chamber is equipped with a pump stand consisting of a 400 l/s (N_2) turbomolecular pump and a pressure sensor for continuous pressure sensing, which means that pressures below 10^{-10} hPa can be reached. A heating facility allows bake-out temperatures up to 200 °C.

Fig. 7 Small vacuum chamber test facility at PI miCos

4.2 Large vacuum chamber

A large chamber with a volume of 260 l is designed for large stages up to a length of 800 mm and for multi-axis systems. A pump stand with a 700 l/s (N_2) turbomolecular pump and a pressure sensor allows tests down to 10^{-9} hPa. With the integrated heating system, bake-out temperatures up to 150 °C are possible.

Fig. 8 Large vacuum chamber test facility at PI miCos

For in-vacuum operation tests on stages, flanges of different sizes are available with various feedthroughs for motor current, scaling system, limit switches, temperature sensors etc. If interferometric measurements are required, or visual observation of processes is necessary, both chambers can be equipped with inspection windows (as shown in the photograph of the large chamber). A quadrupole mass spectrometer (see small chamber photograph) for real-time residual gas analysis (0 amu to 200 amu) is available, which can be attached to both chambers.

5 Vacuum Quality Control at PI

PI classifies and verifies the vacuum products by vacuum pressure measurements and residual gas analysis in the vacuum chambers. Depending on which vacuum level needs to be reached, the chambers and stages are baked out if necessary.

Parallel to pressure measurements, residual gas analysis scans are performed at important points during the vacuum test. Residual ionized molecules in the chamber are separated in the mass filter of the spectrometer. A downstream Faraday cup with secondary electron multiplier allows measurements with low pressure detection limits. Outgassing of water, hydrocarbons or other impurities can be determined, but the desorption processes can also be traced and (virtual) leaks can be detected.

6 High Vacuum Measurement

Fig. 9 Hexapod HP-140 high vacuum version

As an example for a relatively large contamination potential, a high-vacuum version of the HP-140 Hexapod, a 6-axis parallel-kinematic device, is tested inside a vacuum chamber. The results are shown in the following graphs. A pump-down pressure curve for the HP-140 Hexapod is recorded using the small chamber (10 l, 400 l/s pump). After pumping down for two days, a final pressure in the order of 10^{-7} hPa is reached.

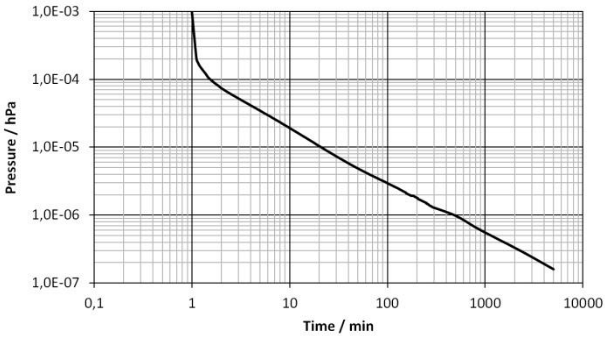


Fig. 10 Pump-down pressure curve of HP-140 (HV). After pumping for two days, a final pressure in the order of 10^{-7} hPa is reached.

A residual gas analysis was made after 48 hours pumping time and shows a spectrum, which is dominated by the water peaks (16 amu to 18 amu), followed by the hydrogen signal (1 amu to 2 amu). The next most dominant signal was caused by nitrogen (28 amu) with about 2% of the water peak intensity. All other contributions are in the order of less than 2% of the water peak. Nevertheless, hydrocarbon contributions are observed over the full range of measured masses and sum up to a considerable HC partial pressure.

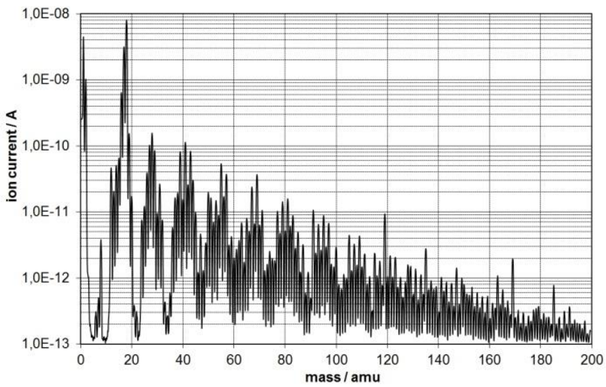


Fig. 11 RGA scan of HP-140 (HV). In addition to the strong water peak at 18 amu, a considerable contribution of HCs is observed.

7 Ultrahigh Vacuum Measurement

For ultrahigh vacuum stages, the pump-down period in the vacuum chamber is followed by a bake-out process of several hours or days, depending on the size of the stage. The stage is kept in thermal contact with the vacuum chamber, which is heated. The allowed bake-out temperature lies between 80 °C and 150 °C, determined by the components the stage is assembled from. Additionally, because all vacuum motors outgas during operation and motor warm-up, the motor of the stage is heated by applying current to the motor coil to gas out most of the residual volatile compounds. The motor temperature should be about 40 K to 50 K above the overall bake-out temperature, and is controlled via an integrated temperature sensor. Furthermore, the motor should be moved slowly during the whole bake-out process. In this way, homogeneous heating of the motor and therefore continuous bake-out of the volatile compounds is ensured. As an example for an UHV product, vacuum test results from the PLS-85 linear stage are shown below. This measurement is made in the same chamber as previously mentioned (10 l, pump 400 l/s). After a pump-down sequence of 15 hours, the stage was heated for 8 hours at 150 °C.

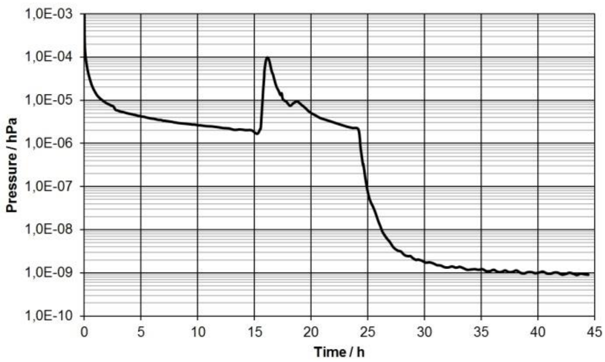


Fig. 12 Pump-down pressure curve of PLS-85 (UHV)

When switching the heater on, the pressure in the vacuum chamber increases by almost two orders of magnitude, and slowly decreases during the heat-out period. After switching the heater off, the effect of bake-out can be observed: the pressure in the vacuum chamber decreases by more than three orders of magnitude, reaching pressures below 10^{-9} hPa at room temperature.

After the cool-down period, a residual gas analysis spectrum was made. In the spectrum, hydrogen (1 amu to 2 amu) dominates, which is hard for a turbo pump to remove. All other signals are at least 10 times smaller. Hydrogen is the exception and water still makes the largest part of residual gas. However, it exceeds other contributions by a factor of two instead of fifty, as in the example for HV. Hydrocarbons are strongly reduced but above 91 amu, there are practically no significant values in the spectrum.

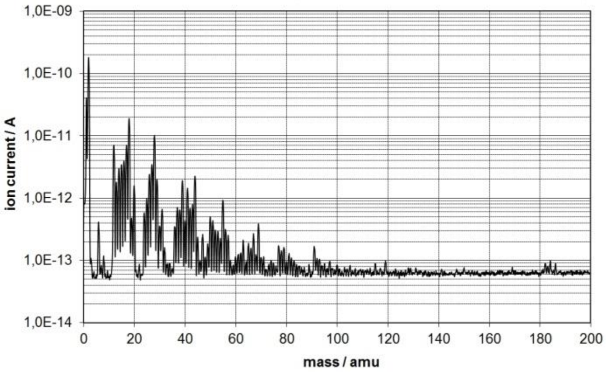


Fig. 13 RGA scan of PLS-85 (UHV). Contributions of HCs above 91 amu can be neglected. The water peak at 18 amu is comparable to other contributions.

8 Shipment and Operation

Instructions for unpacking and handling are labeled to the final packaging.

8.1 Unpacking

Before unpacking the product, the outer bag must be wiped clean. The outer bag must be removed (only the outer bag) before the product is moved into the clean area. The inner bag must be opened using cleanroom gloves and the product must be taken out and kept in the clean area.

8.2 Operation

Before the desired vacuum level is reached, conditioning of the stage in vacuum environment must be performed, depending on the vacuum class of the stage purchased.

In the case of **HV stages**, it is usually sufficient to pump for a couple of hours or days to reach the HV vacuum level, but this depends on the size of the stage and the pumping capacity of the vacuum pump. Motor bake-out by running the motor supports the outgassing process. The stage is designed for temperatures up to a maximum of 80 °C.

For **ultrahigh vacuum** stages, the pump-down period should be accompanied by heating of the stage and the vacuum chamber, as well as additional bake-out of the motor by current feed. For temperature control of the motor, the UHV motors are equipped with a temperature sensor. During heating, the temperature of the motor should be 40 °C to 50 °C above the stage temperature. The heat-out process of several hours or days also depends on the size of the vacuum stage and the capacity of the pump. A good thermal contact to the heated vacuum chamber is essential for a satisfying bake-out result. After cool-down of the vacuum chamber, the desired vacuum level is reached.

9 PI Standard Vacuum Categories

Most of PI standard stages can be used in atmospheric pressures down to 10^{-3} hPa and in some cases even below that. For the range between 10^{-3} hPa and 10^{-6} hPa, vacuum-enhanced standard stages are available (10^{-6} hPa, HV). For higher demands on cleanness and lower pressure (down to 10^{-7} hPa), high-vacuum (HV) stages are available. Pressures below 10^{-7} hPa and down to 10^{-9} hPa or better are reached by the ultrahigh vacuum (UHV) stages.

The components used for the different types of vacuum stages are listed in the following.

HV stages up to 10^{-6} hPa exhibit the following features:

- Vacuum adapted motor
- Standard encoder/read-out system, if required
- Standard wiring
- Standard connectors
- Standard limit switches
- Motor cable made of PTFE-insulated braids
- Aluminum parts are anodized (black)
- Vented screws
- Sliding elements lubricated with vacuum grease
- Bake-out temperature at max. 80 °C

For **HV stages up to 10^{-7} hPa**, materials are used as follows:

- Special HV motor
- HV encoder/read-out system, if required
- 2m polyimide or PTFE braids and HV Sub-D connectors
- Vacuum limit switches
- Aluminum parts are not anodized
- Stainless steel screws are silver-coated, with degas drilling
- Bearing and driving elements made of hardened stainless steel and lubricated with vacuum grease
- Brass alloys if required
- Specially selected plastics
- Holes are vented

For **UHV stages up to 10^{-9} hPa**, materials are used as follows:

- Special UHV motor with temperature sensor
- UHV encoder/read-out system, if required
- 2m polyimide braids and UHV Sub-D connectors
- Special UHV limit switches

- Aluminum parts are not anodized
- Stainless steel screws are silver-coated, with degas drilling
- Bearing and driving elements made of hardened stainless steel and lubricated with vacuum grease
- No brass alloys
- No plastics, except PEEK
- Holes are vented

Electronic devices such as controllers, amplifiers, and others supplied by PI are not designed for in-vacuum use. Therefore, they must be placed outside the vacuum chamber. Suitable feedthroughs and cable adaptors can be provided by PI.

10 Sales Service and Customization

Because many parameters for vacuum applications must be taken into account before ordering, a thorough review of technical requirements will be performed to determine the best possible solution. Grease and/or oil lubrication is present in all vacuum stages with the exception of oil-free UHV-conditioned stages. Oil-free, UHV vacuum conditioning is available for a selection of stage models. Most stages can be equipped with optional linear encoders (angular encoders for rotary stages). Initially, a standard vacuum positioning system is selected to meet the customer requirements. If this selection is not satisfying, alternative customized products can be designed.

Further accessories such as flanges, feedthroughs or connectors are available for PI vacuum positioning systems. Please contact PI for specifications and pricing.

11 Experience with Vacuum Technology

For close to 20 years, PI miCos has applied its extensive vacuum and cryogenic experience to the motion technology field. We supply high precision positioning components and systems for vacuum levels from 10^{-3} hPa to 10^{-9} hPa or lower. Most of our standard products are designed with vacuum applications in mind allowing us to easily make our broad range of stages to be vacuum compatible. We also apply our vacuum expertise to multi-axis turnkey system solutions.

Most of our stages, SpaceFabs, and Hexapods can be prepared for 10^{-6} hPa and 10^{-7} hPa (HV) to 10^{-9} hPa (UHV) as well as for other vacuum levels. UHV products are often particularly suited for harsh conditions such as occuring in X-ray or UV applications. In addition to vacuum applications, we offer components and systems for cleanroom use, cryogenic applications and various other special environments.

Author

Dr. Jürgen Gallus is responsible for vacuum technology research and development at PI miCos. He has many years of experience in vacuum technology and applications.

About PI

In the past four decades, PI (Physik Instrumente) with headquarters in Karlsruhe, Germany has become the leading manufacturer of nanopositioning systems with accuracies in the nanometer range. With four company sites in Germany and eleven sales and service offices abroad, the privately managed company operates globally.

Over 850 highly qualified employees around the world enable the PI Group to meet almost any requirement in the field of innovative precision positioning technology. All key technologies are developed in-house. This allows the company to control every step of the process, from design right down to shipment: precision mechanics and electronics as well as position sensors.

The required piezoceramic elements are manufactured by its subsidiary PI Ceramic in Lederhose, Germany, one of the global leaders for piezo actuator and sensor products.

PI miCos GmbH in Eschbach near Freiburg, Germany, is a specialist for positioning systems for ultrahigh vacuum applications as well as parallel-kinematic positioning systems with six degrees of freedom and custom-made designs.