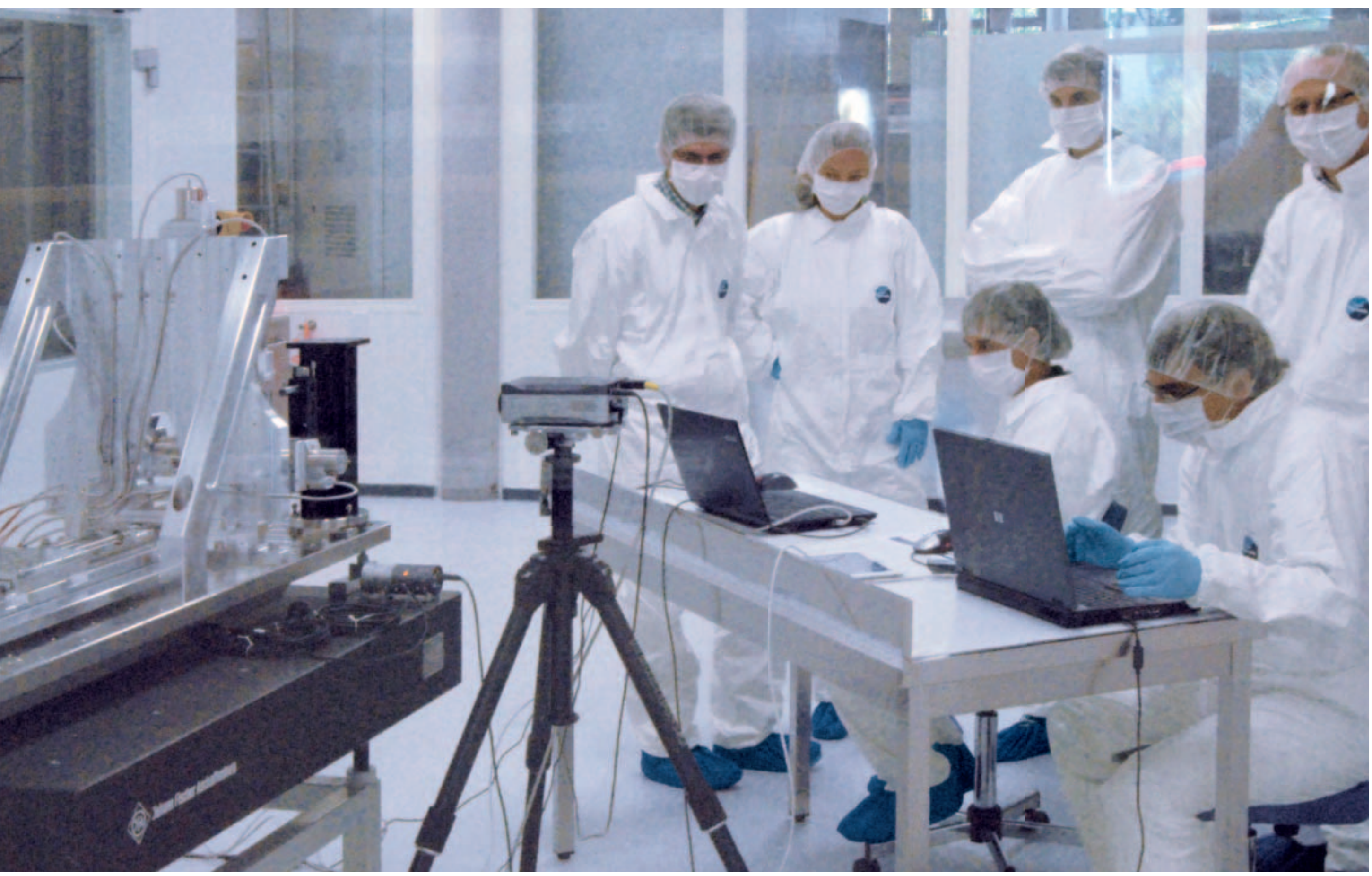
Experimental setup of nanotomography at the P05 beamline, PETRA III, DESY research center (German Electron Synchrotron) in Hamburg, Germany (Image: PI / HZG)

Precision Motion Control

FOR BEAMLINE INSTRUMENTATION

Challenges & Solutions

What Makes Beamline Instrumentation Such a Tricky Task?



Commissioning of a vacuum-compatible multi-axis system and qualification on site (Image: HZG / DESY)

Searching for the Perfect Position for Unique Results

The instrumentation of the individual experimental stations is highly specialized. Nevertheless, common denominators can be named: highest quality, high spatial resolution, position repeatability and long-term stability, motion with a large number of degrees of freedom, and in many cases adaption to vacuum environment to 10^{-9} hPa and below, are key requirements of the positioning devices. Besides, the whole system needs to be addressed and controlled o ver well-known interfaces, and behave in a both predictable and reliable way.

Many, many axes of maybe different drive types need to communicate and act with reference to each other, which requires a most advanced motion control strategy. Travel ranges and positions determine the behavior of other system parts, not only within one platform as is the case in parallel kinematics, but also for other relations when the sample has to be positioned ideally in the beam, when the detector requires a position under a certain angle or in a certain distance, when capillary optics, zone plates, or other focusing optics like refractive compound lenses, filters and masks have to be adjusted within very little space, and to unequalled precision.

Manufacturing quality to the tiniest detail

Cooperation From the Scratch

Close collaboration with the scientific staff at universities and research centers and sharing a common language is very helpful to develop complex, application-oriented solutions for their research needs. At PI, physicists and engineers with a background in research are ready for challenging enquiries. PI also handles installation and qualification on site until the full acceptance of the delivered solution.

Engineered Systems That Use Top-Quality Components

The key to success is that the entire knowledge and experience of the PI family is used for creating customized products for diverse applications. Customized solutions are made easy with the broad portfolio of standard products available from one supplier.

The full instrumentation of an endstation can be ordered from one hand. This gives our customers the assurance that all axes, components and auxiliary devices are coordinated in a most convenient way to the most convincing result.

Mechanical optimization and elaborate design sum up to satisfy the most demanding tasks. From the granite base to the sample manipulator every part of an instrument is selected with profound knowledge, and operated and controlled with consideration.

Challenges & Solutions

Core Competences

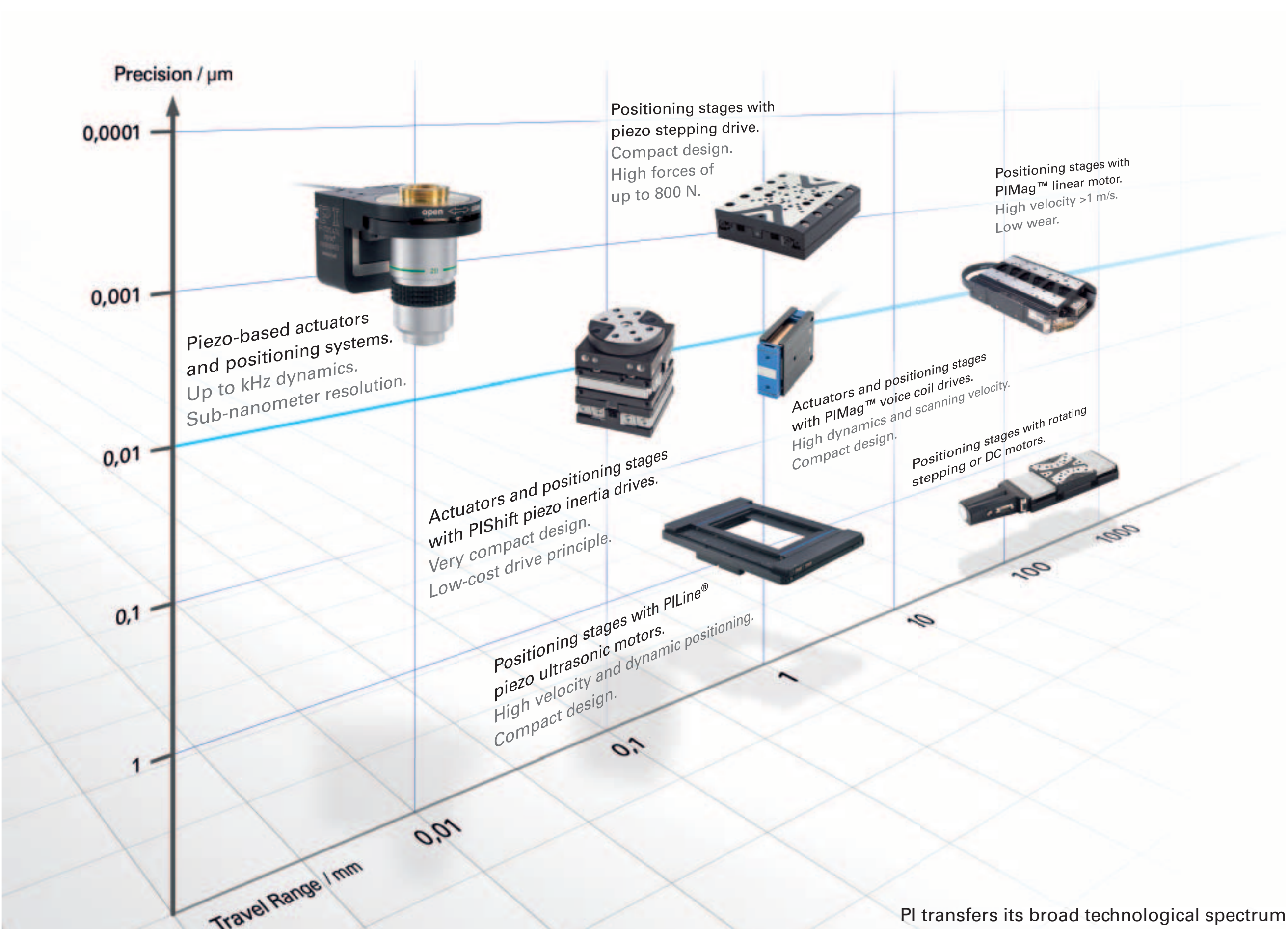
- Commissioning of full instrumentation or single components, turn-key solutions
- Thorough application knowledge
- Complex multi-axis designs, parallel kinematic robotics
- Careful assembly to mechanical perfection
- Variety of drive technologies: linear, torque, stepper, DC, piezo motor
- Motion control electronics and software platform
- Software integration with drivers and DLLs for TANGO, EPICS, spec, LabVIEW, ...
- Proprietary and integration of third-party mechanical, motion and control equipment
- Vacuum conditions: UHV-ready delivery
- Air bearings

Technology Leader for Ultra-High Precision Motion and Positioning

The Broadest and Deepest Portfolio

The technological scope of the PI Group is unique worldwide. PI develops, manufactures and qualifies all its core technologies itself. Thus PI is independent of components available on the market and offers individual solutions that go beyond the state of the art. Through its high measure of flexibility, PI plays a pioneering role in precision positioning and enables PI customers to benefit from distinct competitive advantages.

The aim of the PI Group is to expand its pioneering role on the world mark et through advanced positioning solutions. The broad spectrum of technology and the high vertical range of manufacturing available at PI are the basis for further growth and expansion. Novel drive concepts, products and system solutions have led to a continuous growth in market shares and a healthy company development in the past years.



PI transfers its broad technological spectrum to ultra-precision products

Product Overview

PIEZO ACTUATORS AND COMPONENTS, PRELOADED PIEZO ACTUATORS

Large Variety of Versions, Position Feedback, UHV Option,
High Dynamics, Sub-Millisecond Response Time, Picometer Resolution

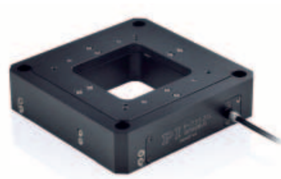
PICMA® multilayer piezo actuators

Preloaded and guided piezo actuators

PIEZO SCANNERS AND POSITIONERS

Nanometer Resolution and Millisecond Response Time

Dynamic steering mirrors



Technology for up to six axes:
Flexure guidings, capacitive position feedback, PICMA® piezo actuators

Piezo scanners:
Fast and precise positioning

PRECISION LINEAR ACTUATORS AND DIRECT DRIVES

Long-Term Stability

Piezomotor linear drive

PiezoMike for long-term positioning without drift

High-load actuators with up to 400 N force for industrial automation tasks

PRECISION LINEAR STAGES

From Miniature Positioning Stage to 1 m Travel

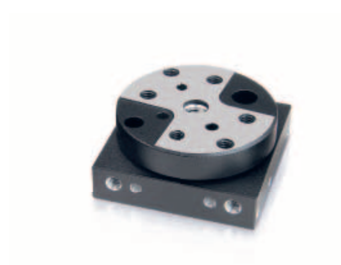
Millimeter size, nanometer resolution:
Miniature stages with piezomotors

High-precision stages

ROTATION STAGES

Ultra-precision Stages or Miniature Form Factor

Ultra-precise with air bearings



Piezomotor miniature rotation stages

HEXAPOD AND SPACEFAB

Parallel Kinematics for Precision Positioning in Six Axes

Precision Hexapods

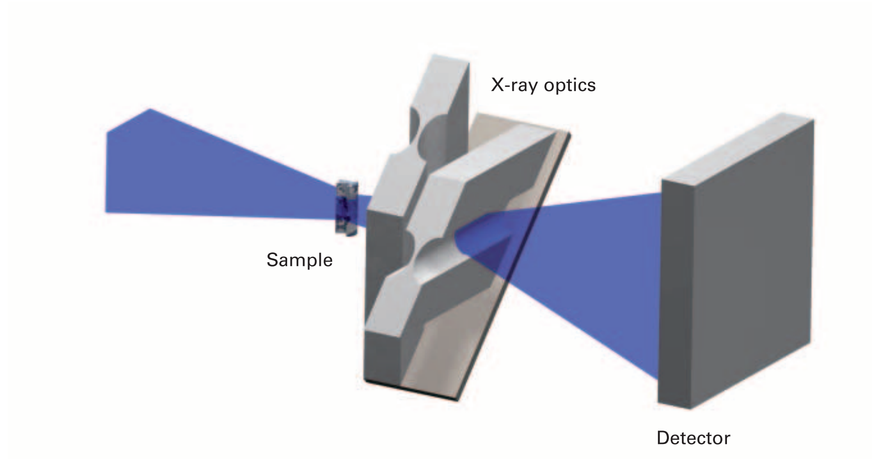
Vacuum versions to 10^{-9} hPa

High-load Hexapods to 1000 kg load capacity

System Success

Tailor-Made Full Instrumentation for Nanotomography

At the X-ray light source PETRA III at the DESY research center (German Electron Synchrotron) in Hamburg, Germany, the Helmholtz-Zentrum Geesthacht – Center for Materials and Coastal Research (HZG) operates the Imaging Beamline P05. The nanotomography endstation on this beamline is designed for nanotomography with a spatial resolution down to 100 nm.



X-ray optics configuration for imaging where the sample is positioned in front of the optics (Image: HZG)

To obtain results on that level a high mechanical stability and precise positioning in the 10 nm-range is required. The instrumentation of P05 beamline had to meet highest demands for mechanical optimization including the selection of adequate feedback sensors and careful selection of all components.

Mechanical Stability Combined with User Flexibility

The full instrumentation setup is based on a 6.8 m long granite bench to minimize the influence of vibrations, topped by four individually moving platforms for sample and detector stages, and X-ray optics for imaging or cone beam configurations.

The substructure itself, which weighs several tons, is also on air bearings. This allows the entire assembly to be moved out of the X-ray beam with minimal effort when the second experimental station is to be used, while maintaining a stable position as soon as the air flow is switched off.

All moving platforms are themselves mounted on air bearings and driven by linear motors. This allows fast and precise positioning of all components.

The whole assembly is moved to the parking position outside the beam on air bearings (Image: PI / HZG)

A Complex Task: Positioning the Sample with Nanometer Precision

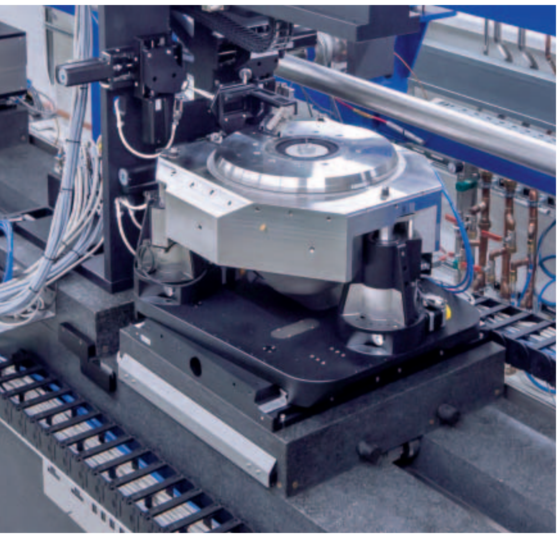
A particular challenge was the construction of the sample stage, since it had to be mechanically stable in the range below 100 nm, in order to achieve the required spatial resolution, to ensure that always the same volume element is investigated when the sample is rotating.

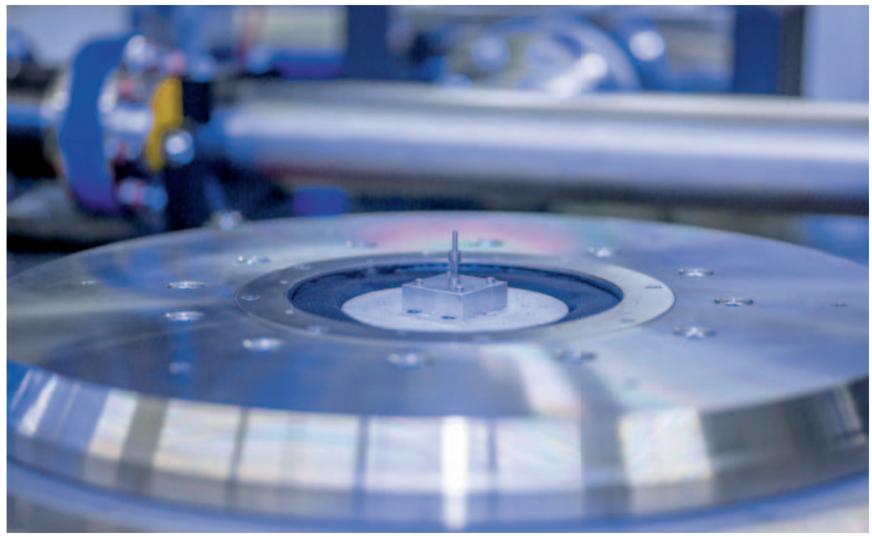
The basis is a horizontal positioning unit which moves the sample stage into the beam. It has a travel range of 20 mm, can be subjected to a load of 300 kg and works with a repeatability of 30 nm at sample position. Stepper motors, precision crossed roller bearings and high-resolution optical linear encoders combined with an adequate motion controller allow closed-loop increments of a few nanometers.

PETRA III is today the most brilliant X-ray source worldwide (Image: DESY / Reimo Schaaf)

Watch details on youtube

System Success





Ultra-precision sample positioning: Z stage, air-bearing rotation stage and a de-coupled 6-axis sample holder (left). The sample holder itself is located in the aperture of the rotation stage on the moving platform of a six-axis parallel kinematics (right) (Image: PI / HZG)

Height adjustment is done with three lifting elements that are also responsible for tilt correction and orthogonal alignment relative to the beam. It is based on three identical, symmetrically ar ranged, worm-gear spindle drives combined with linear scales for direct position feedback.

Mounted on this Z stage is an air-bearing supported rotation stage. What was required was a really „pure" rotary motion of the sample with minimal wobble, radial runout or eccentricity. Only in this case can sharp pictures over 360 degrees be made which all refer to the same volume element and can all be clearly assigned when reconstructing the picture. This is why the rotation stage uses frictionless air bearings to rotate with flatness deviations of less than 100 nm at a resolution of 0.5 µrad.

Sample Holder and Optics Adjustment Using Parallel Kinematics

The sample holder itself is located in the aper ture of the rotation stage on the mo ving platform of a six-axis parallel-kinematic SpaceFAB robotics machine. Essential features are the freely selectable pi vot point of the parallel-kinematic system and its high stiffness.

The SpaceFAB clearly makes work easier for the researchers, since the small samples – only a few 10 to 100 micrometers in size – plus the holder can initially be inser ted into the stage with low precision. They can then be aligned using software commands, not requiring any additional mechanical components for correct alignment.

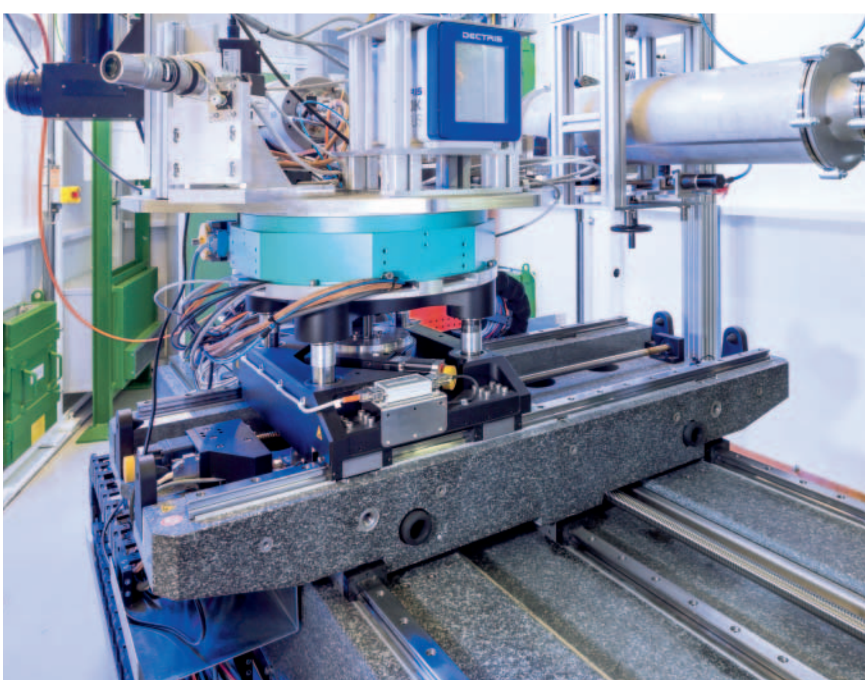
Watch details on youtube

X-Ray Scanning Microscope with Unrivalled Resolution

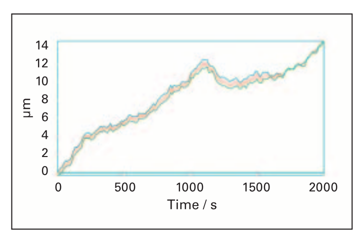
The Hard X-ray Micro/Nano-Probe beamline P06 at PETRA III provides advanced visualisation with micro/nanoscopic spatial resolution using different X-ray techniques. In the Nanoprobe hutch, coherent diffraction imaging applying ptychographic scanning schemes enables X-ray microscopy with increased spatial resolution down to the low nanometer range. Due to the extraordinary brilliance of the PETRA light source, measurements could already be done with spatial resolution of 10 nm only.

No Errors Allowed when Positioning the Detector

A large-scale rotation stage allows to select the different detectors for the particular X-ray techniques. This is carried by a long-stroke XYZ substructure with only minimal vibration influences and tilting errors. The XYZ stage was made from granite to ensure evenness and long-term stability as well as decoupling from environmental influences like vibrations. It provides 2000 mm × 1000 mm × 100 mm linear displacement while the overall position deviation is better than 14 µm. The allowed pitch error was limited to 50 µrad over the full stroke of 2000 mm. Position repeatability if accessed from arbitrary directions is ±1 µm. On-site commissioning and start-up operation were done by PI.

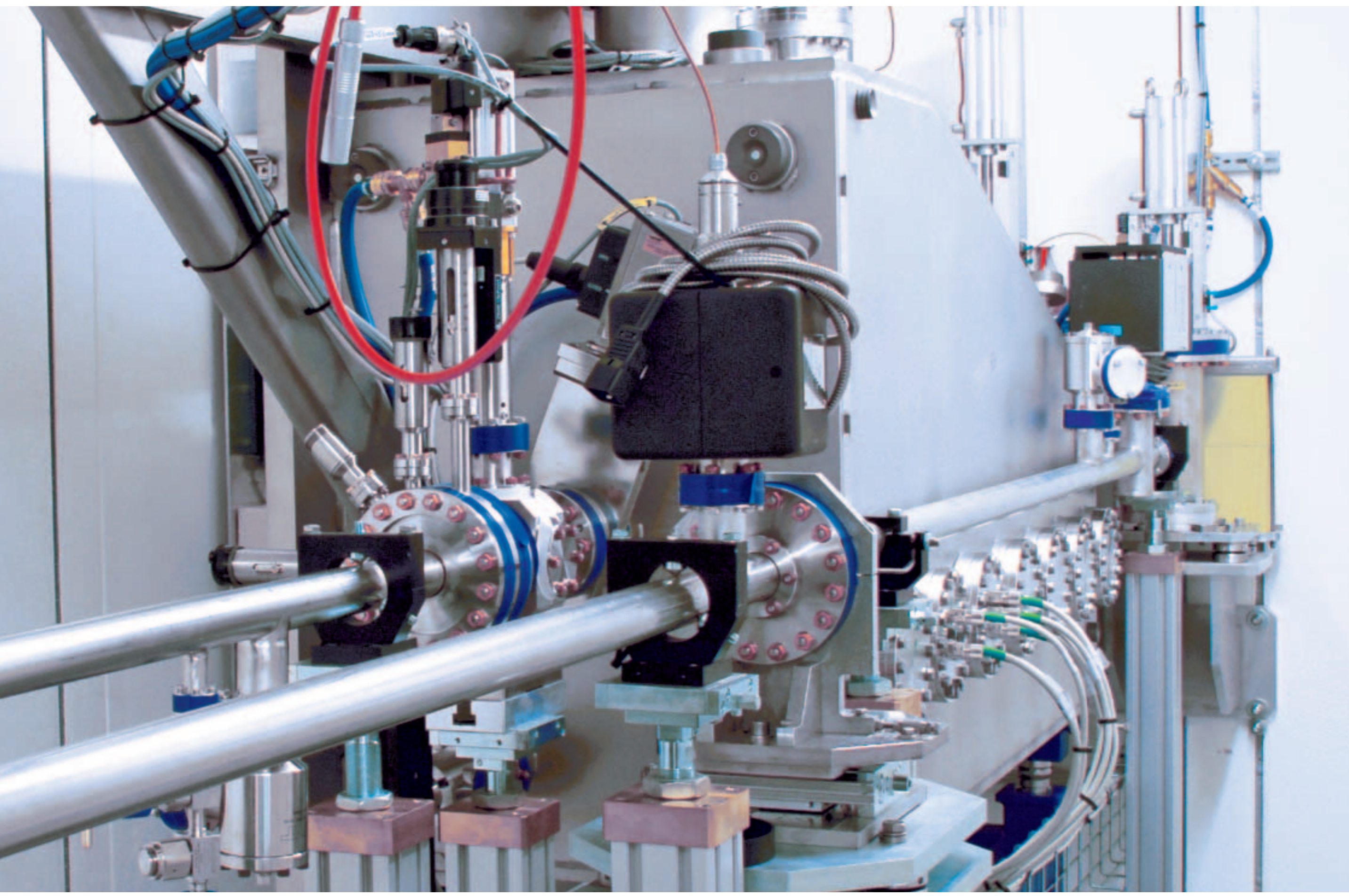


View of the granite XYZ stage with detectors on top (Image: PI / DESY)



The 2000 mm stage proves an overall position deviation of 14 µm, with a bidirectional repeatability below ±1 µm

Optics Hutch Instrumentation



Vacuum chamber design for limited space inside the optics hutch: a sliding door enables access to the instrumentation inside (All images: PI / HZG / DESY)

At the PETRA III light source, located at DESY research center site in Hamburg, Germany, the P05 Imaging Beamline is operated by the Helmholtz-Zentrum Geesthacht (HZG).

Apart from the monochromators and standard optical and diagnostic components like apertures or beam position monitors a large vacuum tank for X-ray lenses and a related aperture is included in the optics hutch. These optics are required for creating a virtual source necessary to operate the nanotomography experimental hutch.

The tank can also hold a diffuser, should this be necessary to reduce beam inhomogeneity or to decrease the degree of coherence.

Vacuum Chamber by PI

The vacuum chamber was designed at PI from the scratch. The limited space inside the hutch set strong constraints on the outer dimensions, while inside the tank, there was the demand for very many moving axes.

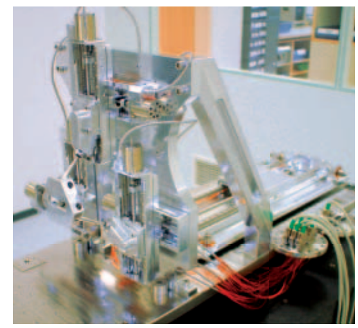
The chamber design includes a sliding door for easy maintenance and provides 0.5 m^3 of space. It is made from stainless steel and holds a vacuum of 10^{-8} hPa. Other features are external reference points for absolute alignment, a manually adjustable chamber stand, and a manually adjustable decoupled base inside the vacuum.

Motion and Positioning Equipment for 10^{-8} hPa

The instrumentation inside the vacuum tank included requirements for four degrees-of-freedom lens alignment and long-stroke positioning of an aperture in the focus. Essential for the application is a long-term position stability combined with a very high positioning resolution. All motion axes had to be decoupled from the chamber. For motion control, a common electronics and software platform was chosen, so all axes are controlled over the same user interface which can be integrated in the hutch's TANGO software environment.

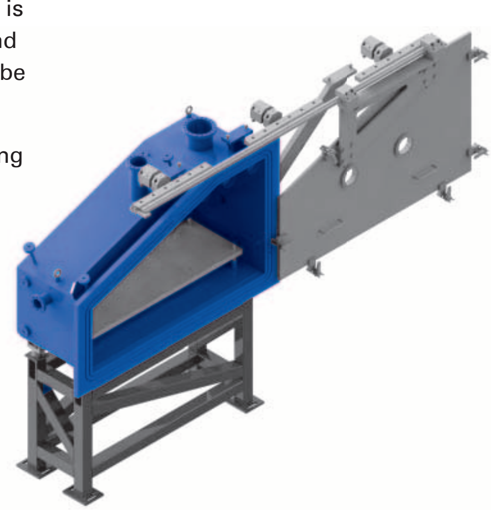
For lens alignment, a parallel-kinematic 6-DOF SpaceFAB robotics was chosen, that allows flexible setting of the pivot point by software. The very stiff design is low-profile and provides the required travel ranges of 50 mm (X), 3 mm (Y) and 20 mm (Z) with a linear resolution of 1 µm. Tilting adjustment in all angles can be done over ±2.5 degrees with a resolution of 0.0003°.

The aperture can be positioned over 500 mm stroke with 10 µm resolution using a customized UHV stage. All axes use UHV-compatible stepper motors.



The SpaceFAB uses UHV-compatible components. The synchrotron beam passes through the aperture in the customized platform and an opening in the mechanical support

SpaceFAB advantage: A long stroke in X allows to place the platform with the lens outside of the beam

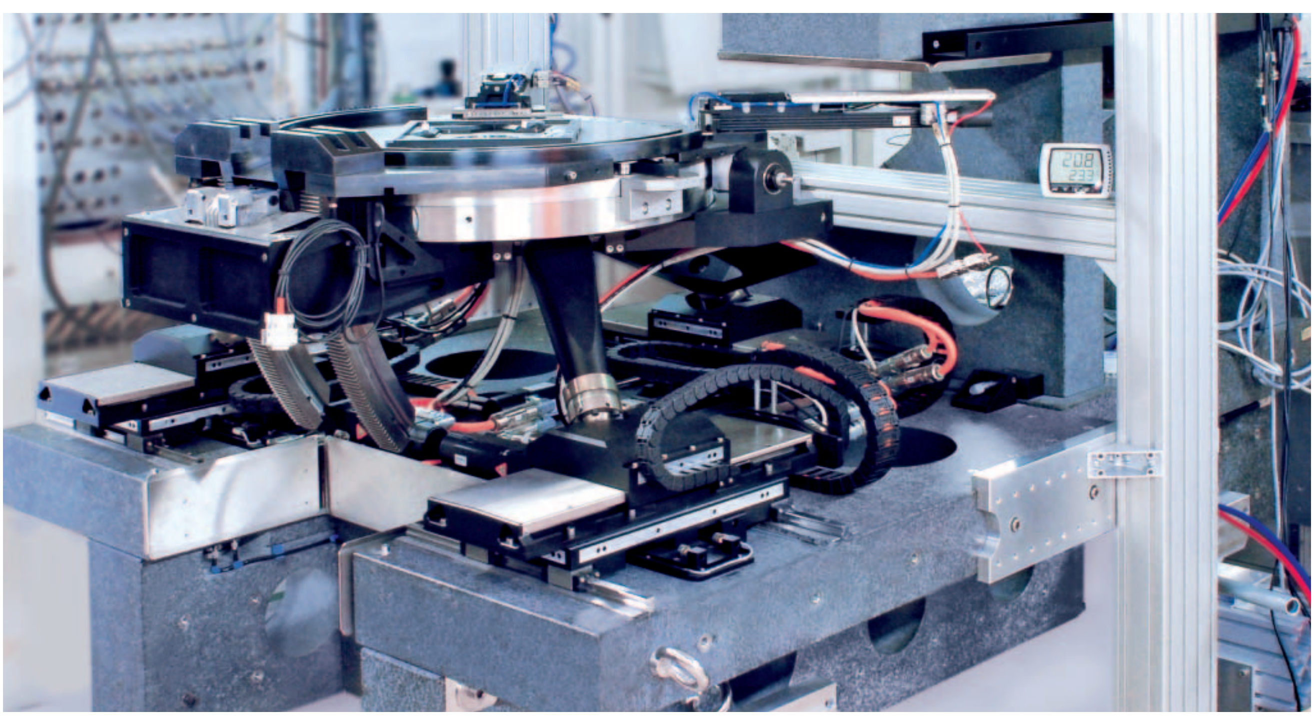


High-Precision Spatial Positioning of Flat, Extended Objects for Laminography

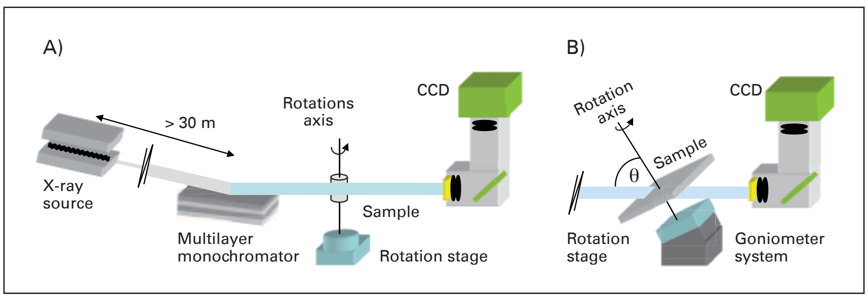
In a joint project, the ANKA (Angströmquelle Karlsruhe) at KIT (Karlsruhe Institute for Technology, Germany), the Fraunhofer IZFP (Institute for Non-destructive Testing Methods, Germany) Saarbrücken / Dresden, Germany, and the X-ray synchrotron source ESRF (European Synchrotron Radiation Facility, Grenoble, France) developed synchrotron laminography, which allows high-resolution 3D imaging on large flat objects. As an example the method is used for examination of composite materials used in wind turbines or in aerospace, for research on their inner structures before, during and after failure. The instrument has been in operation since 2007 at the Beamline ID19 of the ESRF. By means of so-called phase contrast methods it was also possible to successfully examine structures without absorption contrast. At ANKA, the newly commissioned IMAGE Beamline will provide the same method of analysis.

Maximum Demands on Stability and Precision

In laminography, the sample is scanned under rotation around an axis tilted with respect to the beam direction. The volume data can be reconstructed from the different projections. For this purpose, the sample is positioned between the X-ray source and the detector. The requirements are for utmost stability and precision in positioning both detector and sample in this inclined geometry.



Setup of the detector and sample positioning systems as integrated at Beamline ID 19 at the ESRF (Image: PI, Fraunhofer EZRT, ESRF)



Principle arrangement of computed laminography at the Beamline ID 19 at the ESRF (Image: ESRF)

10-axis sample positioner, inclined 45° to the beam

The repeatability of sample positioning following the beam reference measurement has been specified and measured at less than 0.5 µm. Rotation eccentricity also is less than 0.5 µm. This is important so that the various projection angles have the same projected rotation center. At lower accuracy, artefacts would occur during reconstruction.

Positioning Samples with Sub-Micrometer Accuracy

The angle at which the sample is rotated with respect to the synchrotron X-ray beam needs to be adjustable, while the lateral position of the sample itself allows the choice of the region of interest, securely and repeatably.

The solution is a six-axis parallel-kinematic SpaceFAB underneath rotation and tilting stages on which the actual sample carrier is placed. Essential SpaceFAB features are the freely selectable pivot point and its high stiffness. The linear travel ranges are 150 mm × 150 mm × 50 mm, at 0.2 µm position resolution, ±12.5° tilting is possible for the axial angle, and ±5° for the other directions. Precision is provided by optical linear encoders and the high-precision mechanical components which are driven by a combination of stepper motors and ball screws.

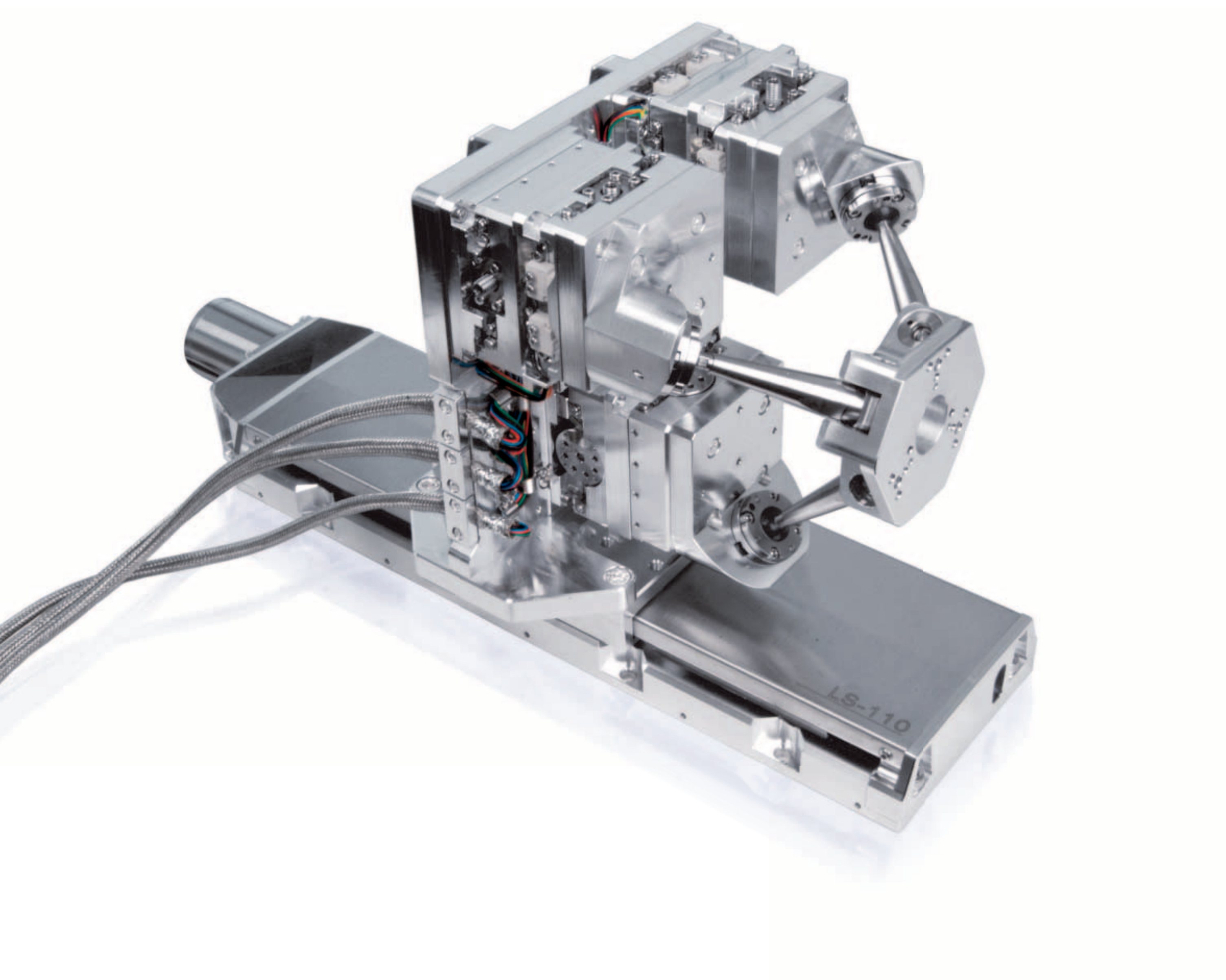
Above, a 360° rotating table enables 0.24 µm absolute flatness deviation only. The angle of the sample relative to the X-ray beam can be adjusted by up to 45° at a resolution of 0.001°. This design has a self-locking rack and pinion drive to remain stable during examination.

The actual sample holder, an extremely thin frame carrier, is held magnetically, a flexure joint and air cushion provide optimal parallelism. Two linear stages shift and center the sample holder over 150 mm × 150 mm but do not touch it during operation.

Watch details on youtube

System Success

Full-Field X-Ray Microscope



At the Beamline U41-TXM of the electron storage ring BESSY II (Helmholtz-Zentrum Berlin, Germany), a novel full-field transmission X-ray microscope (TXM) for the soft X-ray range was set up for the characterization of the nanostructure, chemical nature, and composition of materials on a 10 nm scale.

Additionally to nanotomography, a fluorescence light microscope has been developed that allows correlative microscopy on the same sample even under cryogenic conditions.

Positioning the Condenser Optics

The condenser optics of the X-ray microscope is a glass capillary that focuses the high-energy synchrotron beam to a spot of about 1 µm diameter.

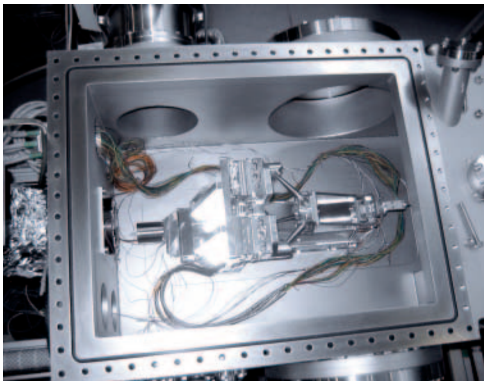
This capillary is positioned using a 7-axis positioning system consisting of a long-range linear stage with a 6-axis SpaceFAB on top. The synchrotron beam passes through the aperture to the capillary condenser optics. Due to the high-vacuum environment of 10^{-7} hPa, all axes are equipped with vacuum-compatible stepper motors. Excellent position repeatability and high stiffness were essential to achieve the required accuracy. The high position stability can be achieved despite a 50 Hz modulation frequency at the tip.

The SpaceFAB's parallel-kinematics design allows for arbitrary setting of the pivot point by software commands. Thus, the operation can be adapted for different focusing optics easily.

Incorporated Fluorescence Light Microscope

Integrated in the same vacuum chamber is a setup for fluorescence light detection. Both analytical methods can thus be performed on the same sample under identical conditions, allowing new insights on the structure.

This setup was commissioned as an addition to the already existing microscope, and thus had to follow the extra limitation to fit into the vacuum chamber. PI designed and delivered the full setup ready to fit into the vacuum chamber, from light funnel to objective positioning to filter change system.



Inside the vacuum chamber: SpaceFAB mounted on top of linear stage (Image: BESSY, HZB)

SpaceFAB Technical Data

- Travel range 10 mm × 10 mm × 10 mm, plus linear stage LS-110 100 mm
- Angular range ±5°
- Resolution < 100 nm, < 10 µrad, open loop
- Environment HV 10^{-7} hPa
- Temperature of samples between cryogenic and 120°

Dynamic Compensation of Lorentz Forces at the XFEL Accelerator Structures

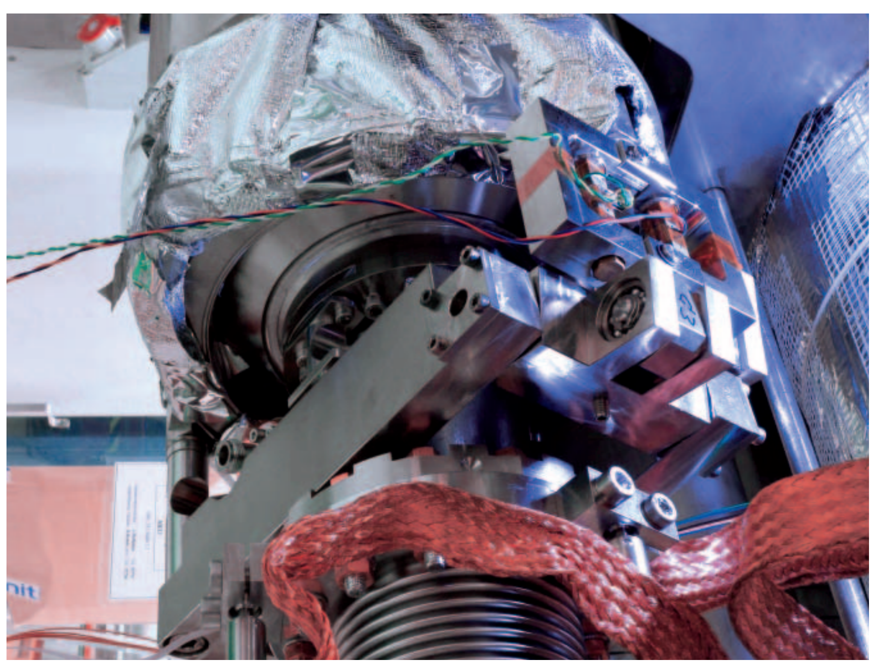
The particle accelerator XFEL at the DESY (German Electron Synchrotron) uses acceleration technology based on super-conducting acceleration structures, so-called resonators or cavities. This technology developed for the linear collider TESLA (Tera Electron Volt Energy Super-Conducting Linear Accelerator) allows the generation of a particle beam with a very small beam cross-section and high beam power. One very important factor is to keep the acceleration field strength at a constantly high leve.

A detrimental effect lies in the acceleration principle itself. The electrons are accelerated in the resonator by electromagnetic fields. The resulting Lorentz force also acts on the walls of the acceleration structure, leading to small deformations, which in turn shift the resonant frequency of the resonators, thus deteriorating the energy transfer to the electrons. This results in higher energy demand and poorer repeatability of the particle beam.

PICMA® Piezo Actuators Reduce Shift in Frequency

PICMA® multilayer piezo actuators work at about four Kelvin directly at the outer wall of the resonator. At these temperatures, the actuator displacement is significantly lower than at room temperature. This effect can be easily predicted and be taken into account when designing the system.

In this cryogenic environment, which is additionally exposed to radiation, the actuators are operated over a long period of use of about 20 years. PI has supplied the actuators already mounted in a preloaded holder, which ensures easy installation.

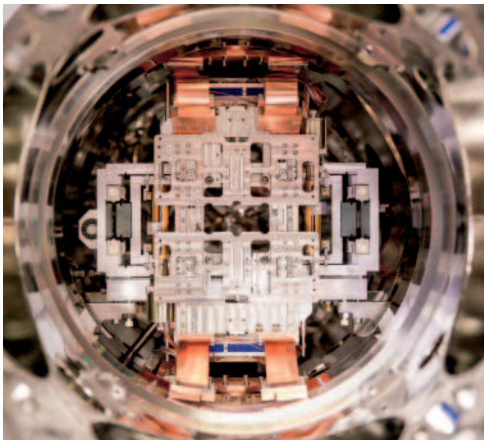


PICMA® multilayer actuators connected to the cavities in a test stand for qualification at DESY. (Images: XFEL / DESY)

Compact Linear Stage Positions X-Ray Detectors

Analyzing the Interactions of FEL Synchrotron Radiation with Matter

The Linac Coherent Light Source (LCLS), part of the SLAC (Stanford Linear Accelerator Center), is a free-electron laser source (FEL) and produces synchrotron radiation of extremely high brilliance. With its radiation, a wide range of new experiments can be effected, e.g. in nonlinear X-ray physics and for single-shot imaging of nanometer structures. At the Atomic, Molecular & Optical Science Beamline (AMO) an experiment to give insight into the interaction of FEL synchrotron radiation with atoms, molecules and clusters is currently being set up.

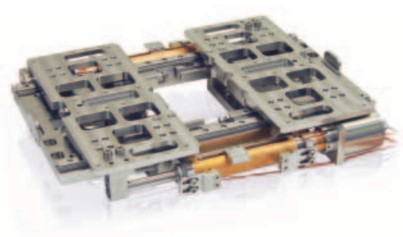


View into the vacuum chamber with the integrated PI stage (Image: SLAC National Accelerator Laboratory)

Reactions that are triggered by laser radiation in the sample are examined using electron and ion spectroscopies or X-ray diffraction. For simultaneously recording scattered X-ray photons on the one hand, and ions and electrons from the interaction of the intense X-ray pulses with the sample on the other hand, a pnCCD camera, which is highly sensitive to X-rays, has to be positioned very precisely and with highest repeatability. The camera records an entire spectrum on one pixel at very high frame rates of 1000 images per second. Due to the parallel architecture of the detector, the main laser beam can pass between the detector parts without damaging them.

Precisely Tuned to X-Ray Scattering

For positioning the two detectors, PI developed a compact linear stage that features a guiding and two separate moving plates. The detectors are able to move independently over a travel range of 50 mm heading towards the 0 „closed" position; the maximum distance between the detectors is 100 mm. The motion of the platforms is controlled by an absolute measuring linear encoder with 50 nm resolution.



A compact tailor-made linear stage positions the X-ray detectors

When positioning both detectors accordingly, the scattered X-rays can be recorded at a wide angle range and can be evaluated spatially and spectrally. The linear stage is designed for ultra-high vacuum to 10^{-9} hPa and is made of stainless steel.

Double-Crystal Monochromator for an X-Ray Spectrometer

The two stages with PiezoWalk® drive and their controllers in the setup (Image: ESRF)

High-Precision Bragg and Tilt Angle Adjustment

At the Nuclear Resonance beamline (ID18) at ESRF, France, a double spectrometer for inelastic X-ray scattering is installed since 2012. Phonon excitation states in solid are investigated with the help of two monochromators that select the desired wavelengths with an energy resolution of 0.5 meV and 2 meV.

Each of the monochromators consists of four independent crystals arranged in pairs. The first pair of crystals collimates the beam, while the second pair selects the beam of the required energy. The width of the respective rocking curves is a few microradian only. To operate in the curve's maximum, i.e. with maximum intensity, the relative angle of the crystals in both pairs has to be adjusted with a resolution of 0.5 microradian or better.

Precise Re-Adjustment of the Crystals

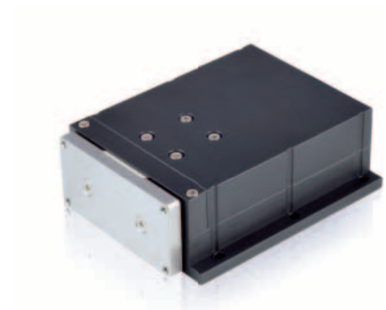
In the course of an experiment, users may need a fast characterization of their samples with a moderate resolution of 2 meV and a high flux and then to select samples for precise measurements with an ultra-high energy resolution of 0.5 meV. This requires a fast exchange of the two monochromators with precise re-adjustments of the Bragg and tilt angles for all four crystals.

Positioning the Crystals Places Exceptionally High Demands

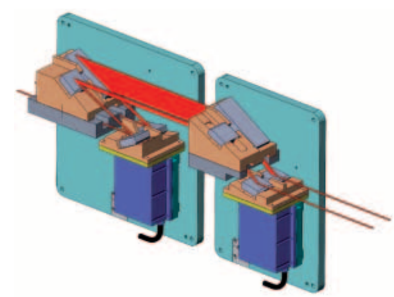
To adjust the Bragg and tilt angle, the crystals had to be moved and positioned with high precision. Additionally excellent long-term stability and very good repeatability were required, while the stages themselves needed to fit into a very limited space.

PI's proprietary piezo-based PiezoWalk® drives with their sophisticated controller provided a perfect-fit solution. Their excellent resolution of 0.1 µrad only in both Bragg and tilt angle, and a repeatability of < 0.1 µrad over a 12 µrad range even exceeded the demands. In combinations with capacitive position feedback sensors that are attached directly to the moving platform, they allow for a long-term position stability well under 0.1 µrad, while the stage's footprint of 95 mm × 78 mm × 32 mm stays very compact.

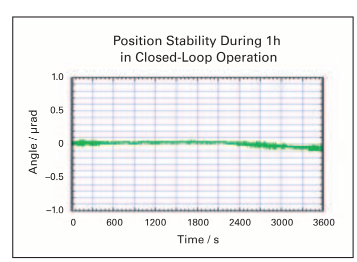
In a future step, the PI stages' angular stroke of ±2 mrad will be used to carry out a synchronized motion to vary the energy selection of the X-ray beam.



PiezoWalk® piezo-based drives make for compact, high-resolution positioners

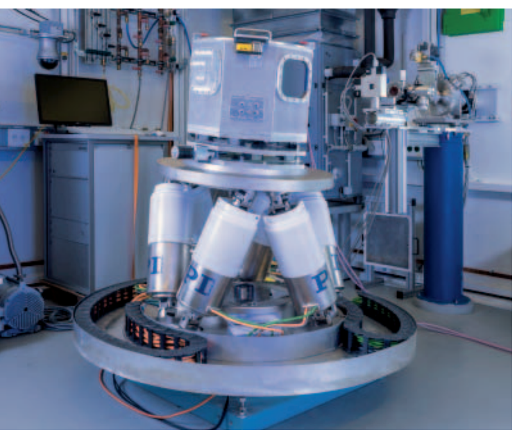


Design of the double monochromator for ID18. The upper crystals are fixed, the angular position of the lower ones are adjusted using a PI PiezoWalk® tip-tilt stage (Image: ESRF)



1 hour position stability of the PiezoWalk® stages: Angular position is kept with a deviation below 0.1 microradian

High-Load Positioning at Material Science Beamline



Here, the Hexapod positions a chamber for laser-welding in the beam (Image: PI / HZG)

P07 or HEMS (High Energy Materials Science Beamline) is one of the first operational lines on the PETRA III light source at DESY, Germany. Since 2010, P07 facilitates diffraction and imaging experiments such as tomography in the high-energy X-ray range of 30 to 200 keV. In-house and development activities are shared by DESY and Helmholtz-Zentrum Geesthacht (HZG).

In experimental station EH3, HZG has specialized in materials research associated with engineering science. For example, complex and dynamic in-situ measurements are conducted of the material properties that occur during reshaping processes such as welding, cutting or heat treatment. The investigation using X-ray radiation indicates the chronological sequence of effects at crystalline level in micrometer-sized domain areas. The infrastructure enables large and heavy sample environments to be created, as well as process chambers, also for external users.

Complete engine blocks, turbine components, sinter furnaces and cryogenic chambers as well as welding fixtures or other machining units need to be aligned precisely for the planned investigations and to be moved accordingly during the analysis. For this purpose a heavy-duty PI Hexapod is used.

Hexapod Positions One Ton in Six Axes with Micrometer Resolution

The parallel-kinematic custom model in use delivers micrometer-precision positioning for loads of up to one ton. It stands approx. 700 mm high and has a diameter of 800 mm (top platform with large aperture) and 900 mm (bottom). The lower platform is installed on a 360° rotation table and the cabling was designed to be dragchain-compatible. With its high load capacity of up to one ton, the Hexapod can carry the entire measurement setup including the device where mechanical forces are applied. The Hexapod positions even these large masses over distances of 400 mm to a precision of ±1 µm, and executes rotational movements of ±20° with a resolution to 0.5 µrad.

Despite the high forces, the position reached is held in a stable manner; the brushless DC motors integrated in the Hexapod struts are equipped with brakes.

Sample Positioning in High Vacuum

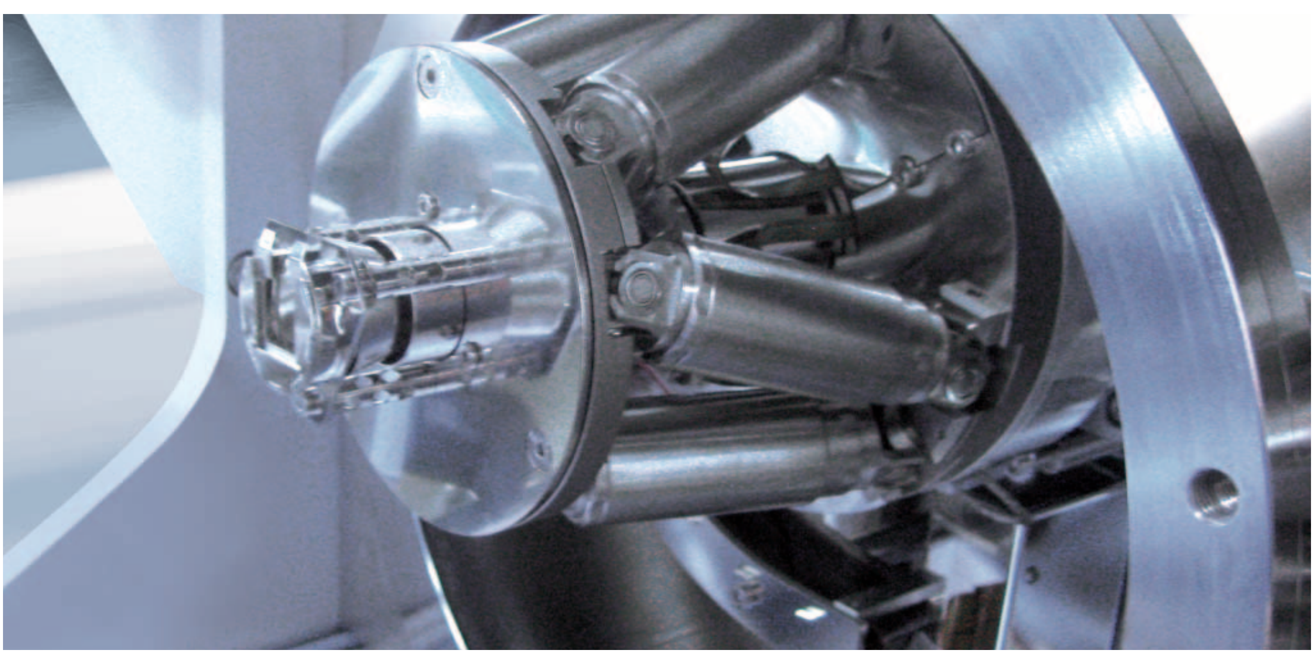
Pulsed Laser Deposition (PLD) In-situ Characterization Using Synchrotron Beams

At the NANO Beamline of the ANKA Synchrotron Radiation Facility (Karlsruhe, Germany), X-ray diffraction and reflections of the synchrotron radiation can be used to investigate the structural properties of thin films under high-vacuum conditions as part of modern material research.

For direct use in the beamline, an all-in-one system has been developed where pulsed laser light is used to tak e the solid target to the gas phase and then deposit it as a layer on a substrate. One c haracteristic of the beamline PLD system is the laser heating, which can heat the substrates up to 1200 °C, and the simple loading. A special feature is the sample manipulator, which allows due to its small size a wide angle range of the X-rays even at low substrate heights.

Hexapod in the Sample Manipulator

In the sample manipulator, a Hexapod, designed by PI for use in high vacuum, positions the samples, i.e. 1 0 mm × 10 mm substrates, relative to the incident X-rays.This allows the sample to be tilted by ±5° around the X andY axes at a resolution of 0.001°. In addition, to compensate for different layer thicknesses, it can be moved in the direction of the Z axis, i.e., vertically to the sample surface, by up to 3 mm. Motions of + / 6 mm in the X and Y directions allow scans at different positions of the sample surface.The Hexapod is mounted on a rotary stage, which can perform further positioning tasks if required.



The sample manipulator allows a wide incident angle range of the X-rays due to its small size even at low substrate heights (Image: SURFACE)

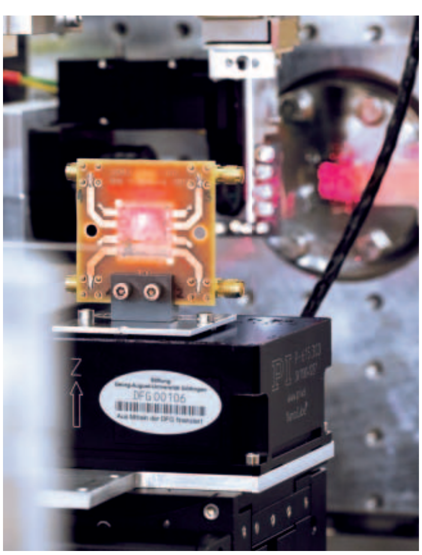
Tomography and Holography Endstation

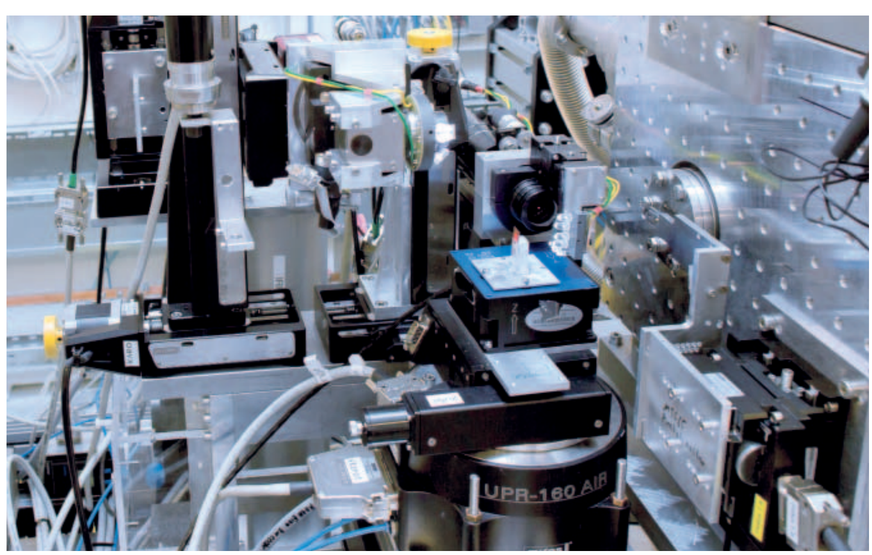
The Beamline P10 for Coherence Applications benefits from the outstanding brilliance of the PETRA III X-ray light source at the DESY research center in Hamburg, Germany. The flux of coherent synchrotron radiation exceeds that delivered by existing storage ring based sources. P10 operates in the medium to hard X-ray regime (5 keV to 25 keV).

The Institute for X-Ray Physics of Göttingen, Germany, operates a Holography Endstation at beamline P10. Their main research aims are directed at the structure, the collective dynamics, the self-assembly and the interactions of biological macromolecules. A particular approach is based on X-ray waveguide optics, enabling the highly localized delivery of X-rays and a quasi-point source for holographic imaging. Thus, spot sizes down to 10 nm have been achieved, and now such X-ray nanobeams can be used for spatially resolved diffraction, and as quasi point sources for holographic imaging.

Scanning with Nanometer Repeatability

PI has provided for the motorized sample positioning setup. A stacked system of XYZ linear axes equipped with stepper motors are used for aligning the rotation axis in the X-ray beam and for distance variation between the waveguide and the sample. Above, a 360 degree high-precision, air-bearing, rotation stage is used for tomography. Upon this basis, a high-resolution XYZ piezo stage for ultra-fine positioning over a stroke of up to 400 µm is used to adjust the sample exactly in the center of rotation, and also enables ultra-high-precision XYZ-scans. With this, on-the-fly measurements of live cells are perfomed scanning an area of 100 µm × 100 µm. A special linearization software inside the digital piezo controller allows for a tracking repeatability in the nanometer range.



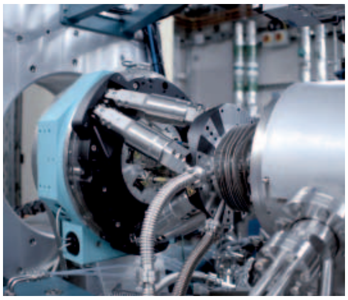


The sample positioning setup inside the holography endstation (right). Left: PI's XYZ piezo stage holding a piezoelectric sample for investigations on collective lipid bilayer dynamics excited by surface acoustic waves endstation (Image: M. Osterhoff, Institute for X-Ray Physics, Georg-August-University Göttingen)

Sample Adjustment inside a Five-Circle Diffractometer

At Diamond Light Source, UK, beamline I07 is a high-resolution X-ray diffraction beamline dedicated to investigate the structure of surfaces and interfaces under different environmental conditions, including, for example, semiconductors and biological films.

In the center of a five-circle diffractometer, the samples are mounted on a Hexapod which provides height adjustment and any other alignment required. The requirements were challenging: Load may easily sum up to 50 kg, while the mounting space within the diffractometer limited the overall height of the Hexapod to 290 mm. Since the Hexapod would operate with horizontally or vertically oriented baseplate, the stiffness of the system was deciding.



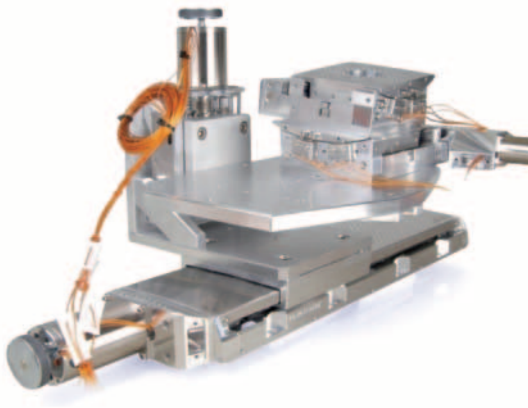
The Hexapod, mounted inside the diffractometer at Beamline I07, provides linear motion to ±15 mm and angular stroke to ±10° (Image: Diamond Light Source)

High-Precision, Long-Term Positioning at 10^{-7} hPa

The ADvanced RESonant Spectroscopy (ADRESS) beamline at the Swiss Light Source (SLS) is a high-performance soft-X-ray undulator beamline operating in the energy range from 300 eV to 1.6 keV. Its RIXS endstation, for Resonant Inelastic X-ray Scattering, is based on SAXES, a high resolution spectrometer for soft X-rays in the 400 – 1600 eV energy range, jointly developed by the Paul Scherrer Institute and the Politecnico di Milano.

The experimental setup uses a VLS (variable line spacing) grating which can be angularly re-positioned to minimize a deterioration of the spectral linewidth by higher order optical aberrations when operating at more than one energy. For this task, a system was designed to move and position the grating in several degrees of freedom: pitch for changing angle, rolling, vertical positioning, and horizontal transverse movement to allow the use of a second, selectable grating.

High accuracy of motion was demanded: Z alignment 32 mm and crystal selection 155 mm with 1 µm resolution each, angular motion over ±5 degrees with a resolution of 20 µrad. Additionally, the whole system needs to be stable over long terms in a vacuum environment of 10^{-7} hPa.



High expectations to meet: Stacked 4-axis positioning of the grating in UHV to 10^{-7} hPa

Components Success

Sample Positioning in Cryogenic High-Vacuum Environment

For research on climate change and glaciology based on dust contained in deep ice core samples from Antarctica and Alps both cold and contamination-free sample environments were required. The instrument operates at cryogenic temperatures of –50 °C in a high-vacuum chamber (10^{-7} hPa).

X-ray Absorption Spectroscopy, X-Ray Fluorescence and X-Ray Diffraction experiments were performed to investigate the structure and the composition of dust. The analysis required a mapping of the extremely complex and inhomogeneous surface of the samples with a precision in the micrometer range. The task was solved using a SpaceFAB positioning robot that provides motion with six degrees of freedom in all linear and angular directions. Tailored for use in high vacuum, the SpaceFAB is very compact, equipped with vacuum-compatible stepper motors, and adapted for use in a temperature range of –50 to +80 °C.

The experiment was part of the CryoAlp project at INFN LNF, Frascati, Italy. Part of this research was carried out at SSRL, a national user facility operated by Stanford Uni versity on behalf of the U.S. Department of Energy, Office of Basic Energy Sciences.

SpaceFAB Technical Specifications

Active axes: X, Y, Z, θ_X, θ_Y, θ_Z

Motion range: ±25 mm (X,Z) ±12.5 mm (Y) ±5° (θ_X, θ_Y, θ_Z)

Bidirectional repeatability: ±0.5 µm (X,Y,Z) ±20 µrad (θ_X, θ_Y, θ_Z)

Minimum operating pressure: 10^{-7} hPa

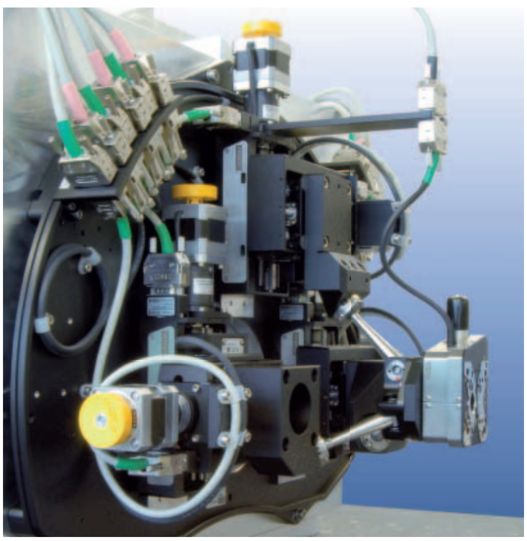
Operating temperature range: –50 / +80 °C

Maximum load: 1 kg

Drives: Vacuum-compatible stepper motors

Absolute position accuracy has been measured to 10 µm (linear) and 50 µrad (angular), with a repeatability of 100 nm and 10 µrad only. The interferometric tests showed an average static stability of up to 20 nm over 1 minute, which allows for thorough examination of the samples.

Full-field Soft X-ray Transmission Microscope



SpaceFAB for Ultra-fine Positioning of the Sample

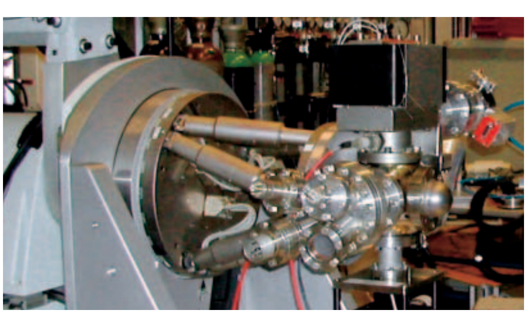
The Beamline 6.1.2 (XM-1) at Advanced Light Source (ALS), Berkeley*, is dedicated to X-ray microscopy and research on nanoscale magnetism.

The sample has to be positioned outside the vacuum, but very close to the beam exit window to avoid absorption in air; "close" being on a scale of some hundreds of micrometers. The spatial resolution of the X-ray beam is 10 nm, so position resolution was requested in the same range.

The solution was a customized 6-degrees-of-freedom SpaceFAB design using stepper motors for excellent position control, plus an elevation stage with down to 50 nm resolution to position the sample in the direction of the beam.

* The Center for X-Ray Optics is a multi-disciplined research group within Lawrence Berkeley National Laboratory's (LBNL) Materials Sciences Division (MSD).

Positioning a Vacuum Chamber for X-ray Diffraction Experiments

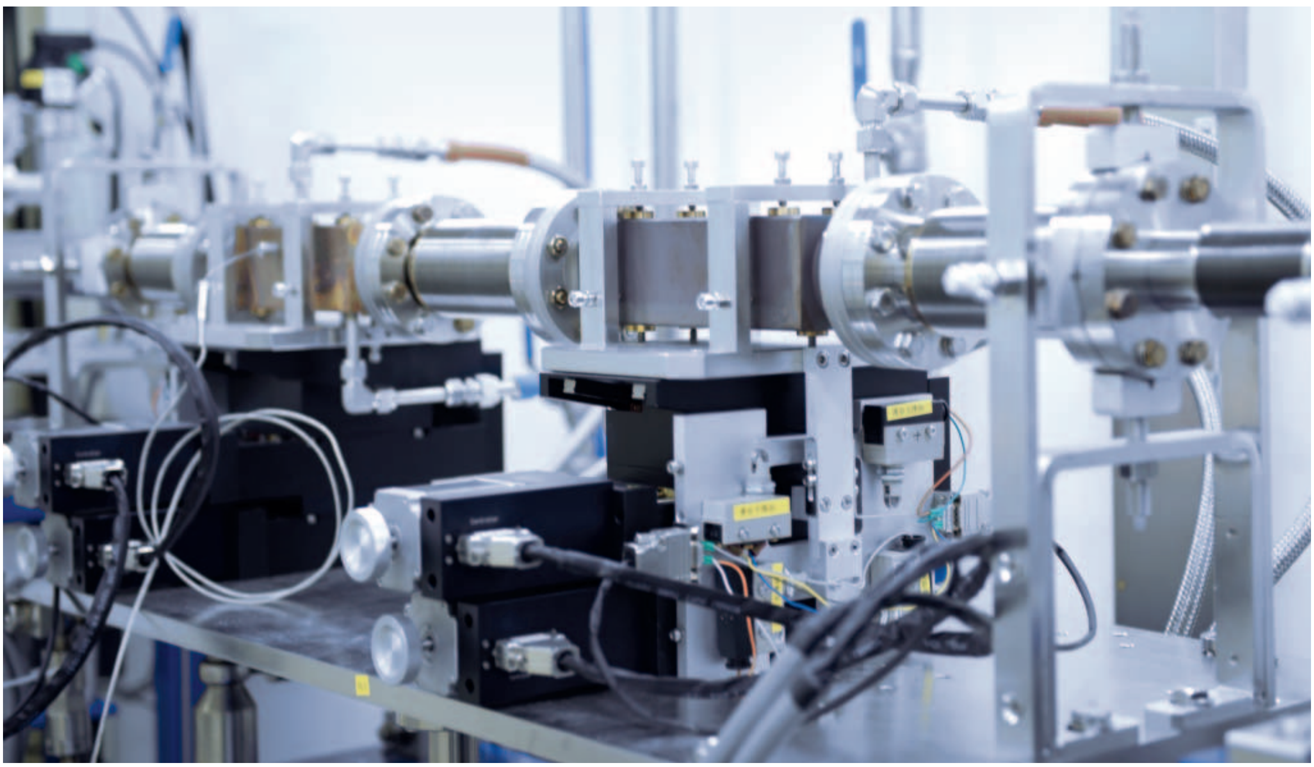


Here, the PI Hexapod carries a UHV chamber for crystallographic experiments in high-energy X-rays (Image: Beamline I811, MAXlab, Lund, Sweden, UHV chamber: Dr. J. Alvarez, Universidad Autonoma de Madrid, Spain)

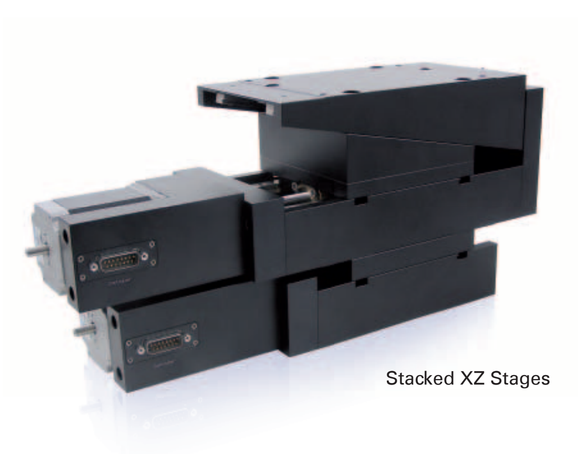
At Sweden's MAXlab, at storage ring MAX II, Beamline I811 is dedicated to materials science research with X-ray absorption spectroscopy and surface science dedicated X-ray diffraction experiments.

For surface, interface, thin film and general X-ray scattering experiments a multipurpose diffractometer is available. Mounted on the diffractometer, an H-850 (formerly M-850) standard Hexapod is used to align the vacuum chamber with the sample in the beam. With its six degrees of freedom, it positions a chamber of 20 to 50 kg with a repeatability of below 1 µm in any orientation.

Slit Control in the Photon Delivery System



View of the setup (Image: PI / courtesy of SSRF)



Stacked XZ Stages

At the SSRF (Shanghai Synchrotron Radiation Facility, Shanghai, China), XZ positioning systems control the optical slits to prepare the beam for experimental tasks. The slit system is working under ambient conditions.

The XZ systems consist of two stacked, high-load, motor-spindle-stages that have been customized to position loads of up to 800 N over a range of 50 mm (X) × 20 mm (Z). The stages are equipped with 2-phase stepper motors and are self-locking. Their cost-effective design includes limit and reference switches.

Sample Positioning for Micro-CT

BAM, the German Federal Institute for Materials Research and Testing („Bundesanstalt für Materialforschung und -prüfung“), operates a hard X-ray beamline at the Berlin electron storage ring BESSY II („Berliner Elektronen-Speicherring Gesellschaft für Synchrotronstrahlung“) together with the German national institute for metrology, PTB („Physikalisch-Technische Bundesanstalt“). The „BAMline“ is intended for X-ray fluorescence analysis, micro-computed tomography, X-ray topography, detector calibration and reflectometry.

Projections for X-ray computed tomography are taken from different angles over 180 ° to collect all data for the reconstruction, while synchrotron radiaton micro-CT requires extremely high precision to ensure that the recorded information always relates to the same volume element. Therefore, the requests for a sample rotation stage were high:

- Highest guiding accuracy
- Flatness and eccentricity < ±100 nm
- Wobble < 2 µrad
- Load capacity 20 kg

PI selected an ultra-precision air-bearing rotation stage to answer these demands. Qualification in-house was executed with capacitive sensors.

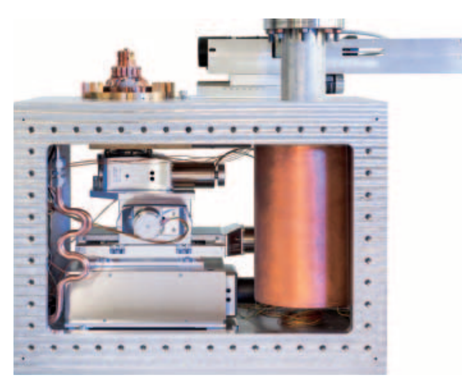
UPR-120 Rotation stage
with air bearings

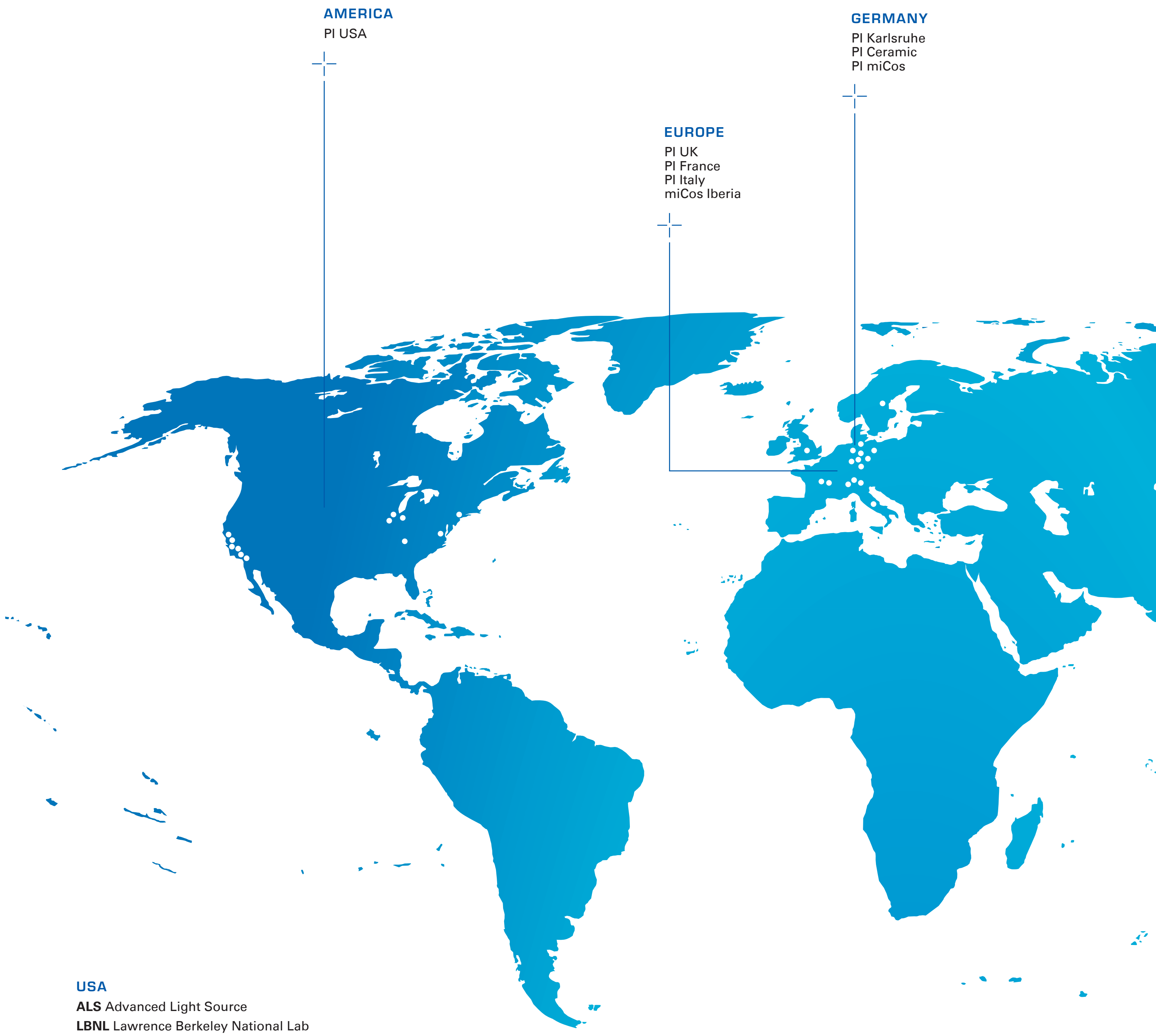
Tomography Stage for Cryogenic Samples

This setup, located at the P06 beamline of PETRAIII at DESY (Germany) allows to investigate samples that require both cooling and vacuum environment.

The sample is positioned using a stacked system of three standard, vacuum-compatible, PI linear stages for XYZ with a 360 degree rotation stage on top. Fine alignment of the sample in XYZ axes is done with an assembly of proprietary piezo motor stages that are equally vacuum-compatible. The setup allows for cooling the sample to the level of liquid nitrogen.

In addition to the motion and positioning elements, also the vacuum feedthroughs were designed and manufactured by PI.





USA

ALS Advanced Light Source
LBNL Lawrence Berkeley National Lab
ANL Argonne National Laboratory
APS Advanced Photon Source
SLAC Stanford Linear Accelerator Center
LCLS Linac Coherent Light Source
LLNL Lawrence Livermore National Laboratory
FERMILAB
JPL Jet Propulsion Laboratory (NASA)
MSL Mars Science Laboratory
ORNL Oak Ridge National Laboratory
BNL Brookhaven National Laboratory

EUROPE

ESRF European Synchrotron Radiation Facility (FR)
SLS Swiss Light Source (CH)
PSI Paul Scherrer Institut (CH)
CERN European Organization for Nuclear Research (CH)
MAX IV Laboratory (SE)
Diamond Light Source (UK)
INFN Istituto Nazionale die Fisica Nucleare (IT)
SOLEIL (FR)

GERMANY

DESY Deutsches Elektronen-Synchrotron
HZG Helmholtz-Zentrum Geesthacht
PETRA III Positron-Elektron-Ring-Anlage III
ANKA Angströmquelle Karlsruhe
KIT Karlsruhe Institute of Technology
BESSY Berliner Elektronenspeicherring Gesellschaft für Synchrotronstrahlung mbH
HZB Helmholtz-Zentrum Berlin
European XFEL X-ray Free Electron Laser

ASIA
PI Japan
PI Shanghai
PI Singapore
PI Korea

ASIA
SSRF Shanghai Synchrotron Radiation Facilities (CN)
SPring-8 (JP)
SACLA XFEL (JP)
PAL Pohang Accelerator Laboratory (KR)

Advanced Research All Over The World

Worldwide, more than 50 synchrotron and FEL light sources are in operation. Attached to them there are several hundreds of beamlines with experimental endstations, each equipped to serve their special task in today's most challenging applications from fundamental research to applied science.

Research groups from solid state physics to art history, from biology and crystallography to surface inspection and material science make use of high-energy X-ray beams.

The methods of the individual experiments show great variation, or combine the different techniques for non-destructive methods often down to atomic scale: Lithography, tomography, diffraction, spectroscopy, microscopy, imaging, and many more.

Well-Positioned

The PI Group is present in all key technology regions worldwide with local representations around the globe. We offer:

- Service facilities and metrology equipment
- R&D departments
- Construction in close contact with customers
- Sales and application experts for the entire product portfolio
- Market and business development experts

Acknowledgements
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DESY Deutsches Elektronen-Synchrotron
European XFEL
HZG Helmholtz-Zentrum Geesthacht
KIT Karlsruhe Institute of Technology
BESSY Berliner Elektronenspeicherring Gesellschaft für Synchrotronstrahlung mbH
Institute for X-Ray Physics, Georg-August-University Göttingen
ESRF European Synchrotron Radiation Facility
PSI Paul Scherrer Institut
MAX IV Laboratory
Diamond Light Source
INFN Istituto Nazionale die Fisica Nucleare
LBNL Lawrence Berkeley National Lab
ANL Argonne National Laboratory
SLAC National Accelerator Laboratory

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