The Monolithic Two Axis Flexure Joined Mirror Support and the Mechanical Design of the Infrared Beamline

T. Noll, C. Kalus, W. B. Peatman, U. Schade, and W. v. Scheibner

BESSY GmbH, Albert-Einstein-Strasse 15, D-12489 Berlin-Adlershof
Phone: + 49 - (30)6392 4655; Fax: + 49 - (30)6392 2990
E-mail: noll@bessy.de

Abstract

At the electron storage ring BESSY a new and innovative infrared beamline has been designed and built for experiments in biology, biophysics and material science. In order to fulfill the stringent stability requirements a basically new mirror moving mechanism had to be developed. This unit is based on a monolithic body which contains two independent segments of rotational symmetric flexure hinge patterns [1-3]. The design provides two rotational axes which intersect the midpoint of the mirror surface normal to each other and parallel to the mirror surface. The flexure hinge patterns interpenetrate in two orthogonal directions. The monolithic body additionally includes the elastically loaded kinematic mirror mount. Its motion is driven by two linear feedthroughs.

Advantages over classical mirror moving mechanisms are: it requires only little space, works very smoothly, producing a high positioning accuracy and is vibrationally stiff. Because of the monolithic design the UHV compatibility is good.

Keywords: mirror support, weak link mechanism

1. The Infrared Beamline: Layout and Configuration

The new infrared beamline at BESSY was successfully commissioned in the first half of 2002 and has since been turned over to user operation [4]. The first part of the beamline is located in the tunnel of the storage ring and the second part on the top of the storage ring tunnel (Figure 1). The related experimental place is also on the concrete tunnel whose thickness is 0.7 m. The first part of the IR- beamline consists of two vertical optical columns and the transverse section between the columns. The first mirror is located at the bottom of the first column in the dipole chamber. It is vertically movable to three positions. The manual valve between the dipole chamber and the first column can be closed if the mirror is in the upper position. In the mid position the mirror is out of the electron storage ring plane and is not thermally loaded from the high energy fan of the synchrotron radiation. In the lower position the mirror is supported in a conical base inside the dipole vacuum chamber. It can be aligned in a small range by tipping the lift rod on the top of the vacuum column. The mirror reflects the infrared light vertically out of the ring plane [5]. The mirror was subdivided in two segments to pass the high energy radiation through to an absorber. To ensure the coincidence of the surfaces of both mirror segments their edges are pressed onto a planar lapped frame which also gives sufficient thermal contact. The mirror support and the mirror itself are made of OFHC-copper. The former is water cooled. The outside surface of the mirror support was rhodium coated to harden it and to reduce friction and abrasion.

The second mirror is located in the upper part of the first column. It has a cylindrical surface to focus the light sagittally just in front of the diamond window above the tunnel ceiling. It reflects the light horizontally through the transverse section to the third mirror, which focuses the light meridonally at the same point.

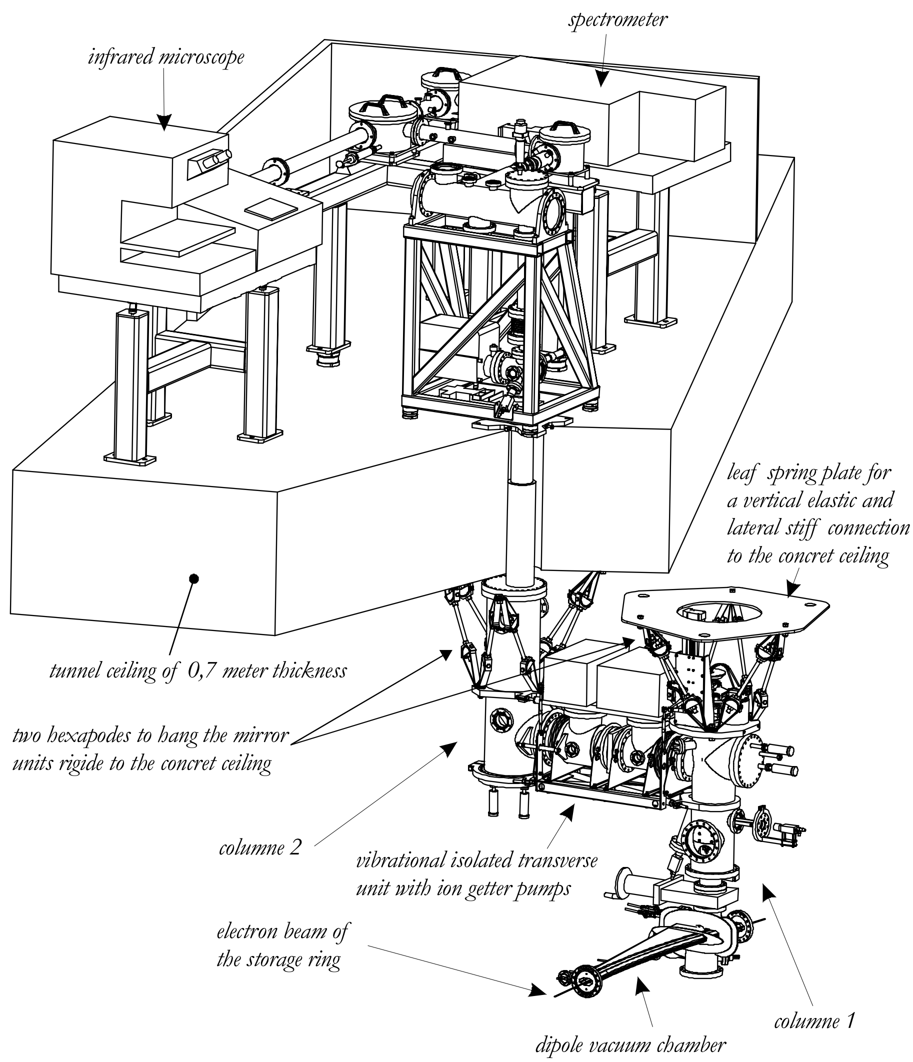

Fig. 1: The infrared beamline, overall view.

In total, the infrared system contains eight mirrors. The remaining five are in the second part of the system on top of the tunnel. An important characteristic of an infrared beamline is its vibrational behavior. The typical experiments are extremely sensitive to vibrations. Hence, the mirrors may not vibrate in the range of 2 Hz - 2 KHz. The columns which are the mirror chambers were mounted on the concrete ceiling with W-type hexapods. Because of the thickness and monolithic character of the concrete tunnel it is a suitable base for that beamline.

The transverse unit of the beamline contains two ion getter pumps to ensure the ultra-high vacuum. A gate valve divides the frontend into two vacuum sections. The pumping unit is separated from the mirror vessels by edge welded bellows on each side and is fixed apart from the optical columns to the ceiling.

The two optical columns must remain in fixed optical alignment with respect to each other and to the source. In order to compensate for thermal expansion, the first column, which is rigidly connected to the dipole chamber at the lower end, is centered and the weight carried by an aluminium plate which provides vertical flexure but is very stiff in the horizontal translational directions. Thus, the aluminium plate supports the main weight of the system and does not over constrain the vacuum vessel. The lower end of the second column is rigidly mounted by a hexapod to the tunnel ceiling. The upper end is centered by a guide bushing on top of the tunnel to allow free expansion of the column in vertical direction. A strut system between the optical columns prevents rotations.

In Figure 2 the W-type hexapods are visible which fix the vacuum vessels to the ceiling. These hexapods must be aligned only once when the beamline is assembled and commissioned. To facilitate the difficult alignment procedure software is used to calculate the changes of each strut in order to move the chamber a specific distance in Cartesian directions.

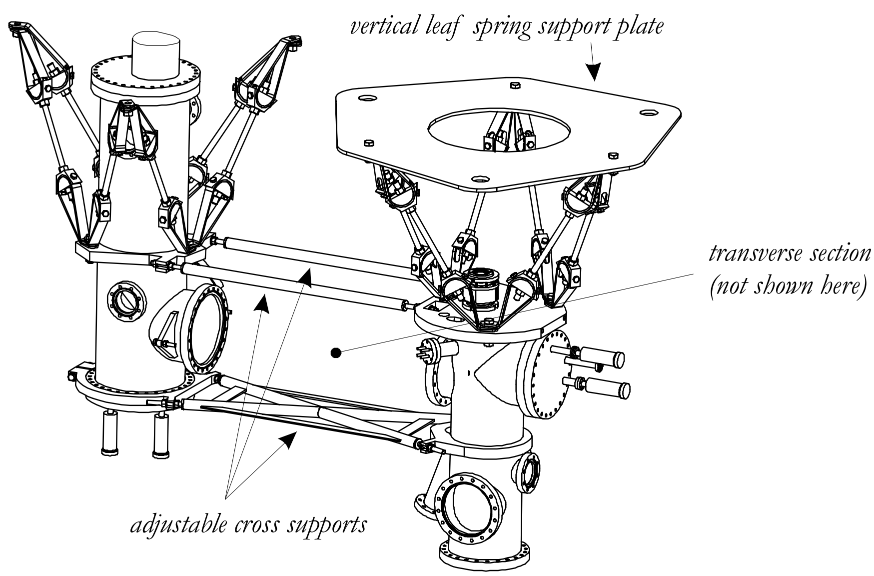

Fig. 2: Structure of the first and second column with cross support.

The mid-part of the struts of the W-type hexapods are threaded rods which are fixed at their ends with two nuts to the heavy sheet metal loops. These nuts were also used to perform the modifications to the strut length. The pitch of the thread needs to be known in order to apply defined movements in a accuracy of tenths of millimeters.

The cross supports between the columns are necessary because of the use of edge welded bellows in the cross section. The nominal size of 250 mm of the bellows produces an air pressure caused force of 4909 N. In addition to preventing rotations of the optical columns the cross struts counter this compression.

2. Vibration Suspension

There are two possible strategies to passively reduce the amplitudes of vibrations. It can be worked with large masses when heavy frames are placed on soft damping mountings. This is the typical method for measuring machines where for example, granite bodies are used as durable base bed for a precision guide system.

A basically different strategy is to use the massive concrete of the tunnel as a base for mounting the optical components as stiffly as possible. The intention is to reduce the relative vibrations between the concrete and the mirrors and thus the relative vibrations between all optical components of the beamline. For this method the maximization of the stiffness of the support is associated with the minimization of the vibrating mass [6]. That model becomes clearer through the analytical equation of the first natural frequency. The cyclic frequency of a nondamped system is:

$$\omega^2 = \frac{c}{m},$$

while the interrelation between the cyclic frequency and the natural frequency is

$$f = \frac{\omega}{2\pi} \quad \text{, where}$$

ω = the cyclic frequency,

m = the vibrating mass,

c = the spring constant of the supporting structure and

f = the first natural frequency.

Following these considerations the vacuum vessel, the frame and the adjustable mirror mount were optimized in order to reduce their mass and to increase their stiffness. The mirror moving mechanism is based on extensive experience with six strut arrangements for Cartesian movements [7-9].

3. The Movable Mirror Supports

The mirror support consists of a lightweight monolithic aluminium body with several features. Along with the static support of the mirror and its elastic mount it works as flexural guidance for two rotations of the mirror. Both rotational axes are parallel to the surface of the mirror, normal to each other and cross at the midpoint of the mirror surface.

Figure 3 shows the adjustable mirror unit and its rotational axes. Stepper motors drive linear motion feedthroughs which are connected to the mirror support by struts with flexure fibre joints at their ends [10,11].

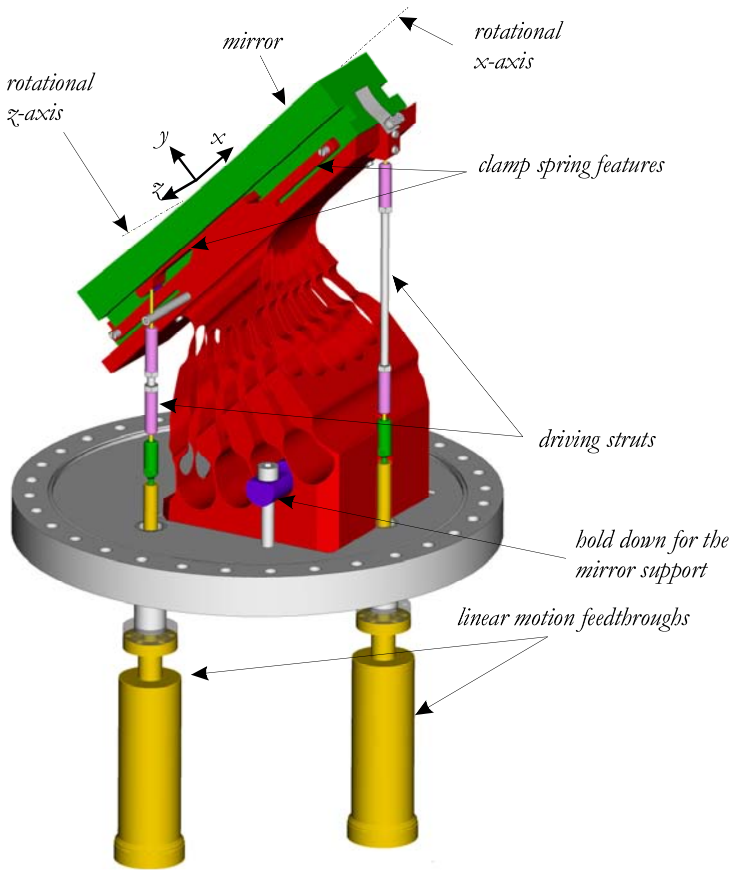

Fig. 3: Movable mirror support of the second and third mirrors of the infrared beamline.

In Fig. 4 the multiple parallel flexure hinge patterns are represented. The systems of each axis interpenetrate in two orthogonal views. The figure shows the monolithic aluminium body without the mirror in two directions. The view planes are normal to the rotational axes to display the mode of action of the strut patterns. The thin dashed lines illustrate the line of action of the single struts and show that the rotational axis of each motion lies in the intersection of the lines of action.

For the rotation around the z-axis five flexure hinged strut rows are operating in parallel. The rotation around the x-axis is guided by seven rows of flexural hinged struts which also work in parallel. The interpenetration of the weak link arrays produces thirty-five single struts where the grooved bending joint zones are located on different positions along each strut. Thus, the joints are essentially no flexure ball joints. The high level of parallelism leads to a high stiffness and reduces parasitic motions [12].

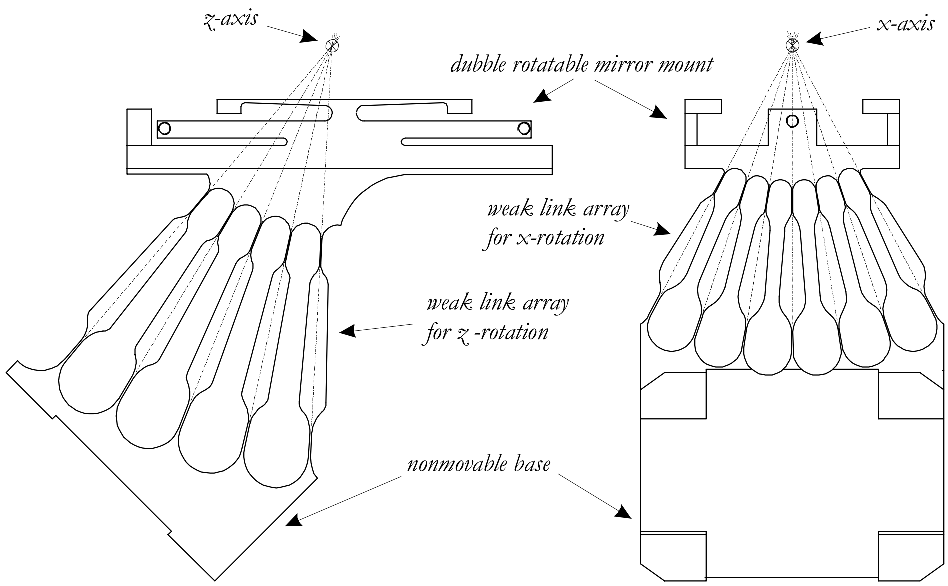

Fig. 4: Two projected views of the flexure mirror support.

The length of the struts and the dimensions of their joints were subject of an optimization in Pro/Mechanica with an enforced displacement of 1° in two axes. The maximal von Mises stress in the joints is 144 MPa. The modal analysis calculates the first natural frequency to be 132 Hz. All joints of the flexure hinge patterns are in the elastic range of the aluminium cast alloy [13] whose ultimate stress is 240 MPa. Thus, there is no plastic deformation and no hysteresis. Because of the safety factor of 1.66 a high number of moving cycles is guaranteed until the first fatigue cracks of single joints occur. Figure 5 shows the exaggerated deformation of a rotation around the x-axis. Manufacturing by milling and erode processes took place in a specialized workshop [14].

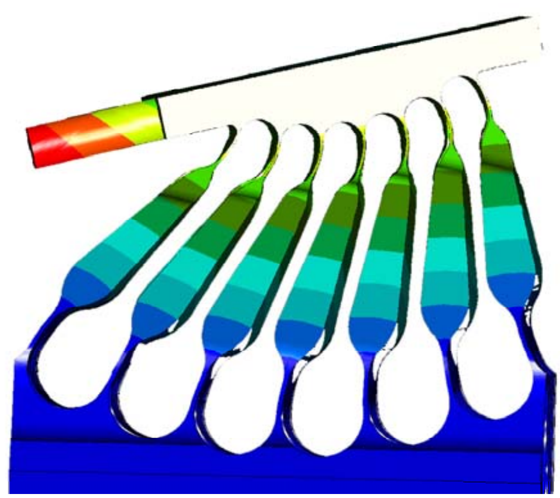

Fig. 5: Deformed pattern of flexure joined struts:
dramatically exaggerated simulation plot of Pro/Mechanica.

4. The Mirror Mount

Figure 6 shows the integrated spring clamp for fixing the mirror elastically. On its backside the mirror lies on three alignment screws with ball contacts. The springy ends of the clamps have coaxial holes in which supporting pieces with a spherical surface are screwed.

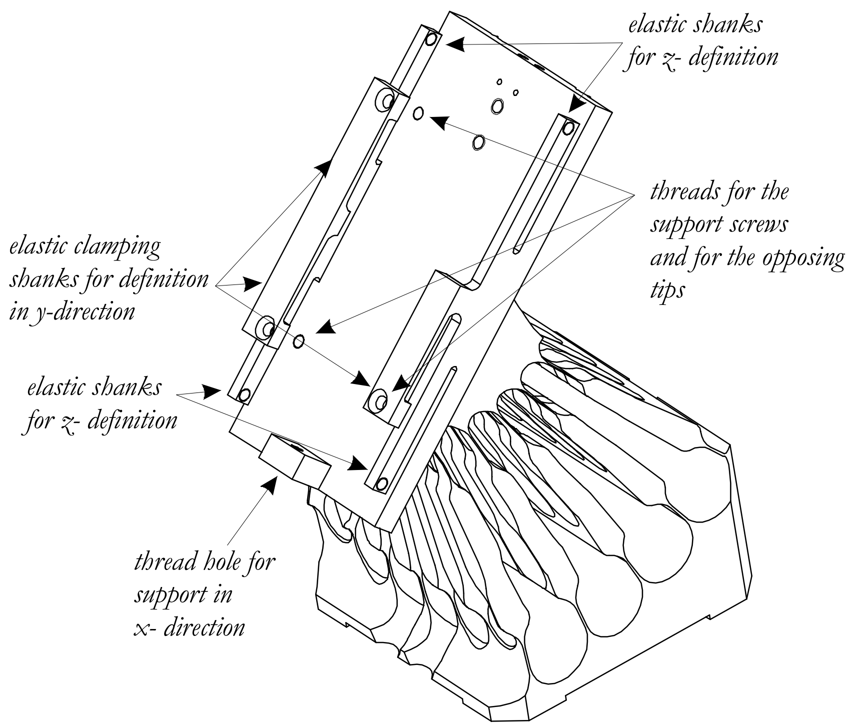

Fig. 6: Monolithic integrated clamp springs for mounting the mirror.

To assemble the mirror the alignment screws must be turned down until they disappear in the bed. The mirror can easily be moved into the t-slot without hitting or scratching any hindrances. After that the alignment screws are turned out in order to fix the mirror elastically and pre-align the mirror on its kinematic mount. The flexure clamp shanks are optimized for an elastic deformation of 1.5 mm with a pressure force of 30 N to assure fixing the Si mirror of a weight of 955 g. The t-slot is closed with a leaf spring (see Fig. 3).

The arrangement of the linear motion feedthroughs (Fig. 7) and especially the strut ends are very important for cartesian movements. The turning lever is given by the distance of the connecting point to the middle of the mirror. The lengths of the lever (l_x and l_z) influence the load on the feedthrough and the angle increment per linear step of the drive. The rotation around the x-axis has to be arranged so that its extended line of influence intersects the z- rotational axis. The drive for the rotation around the z-axis needs to be arranged in a way that its line of influence intersects the x-rotational axis. The closer the connecting points come to the axis the smaller is the motion deviation.

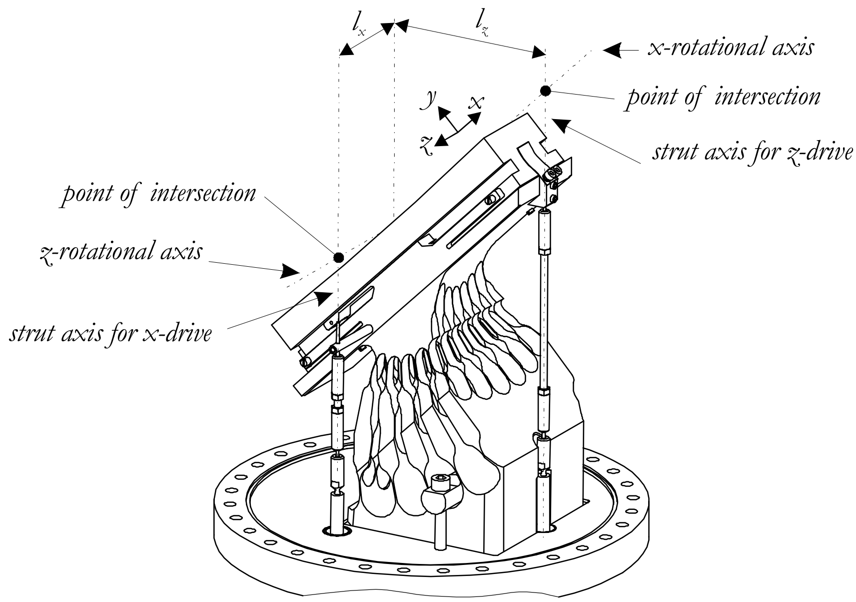

Fig. 7: Mirror support with driving struts; the line of influence of each strut needs to intersect the opposite axis of rotation.

5. Conclusions

For vibration sensitive infrared experiments at the electron storage ring BESSY a beamline with new features has been developed and is presently starting user operation. The reduction of the mass of the components leads to an extremely stiff installation with very small vibration amplitudes and high natural frequencies. An innovative mirror support with two flexure joined rotational axis and integrated features to elastically clamp the mirror has been developed.

6. References

[1] D. Shu, “Ultraprecision Motion Control Technique for High-Resolution X-Ray Instrumentation,” Proceedings of the 1st International Workshop on Mechanical Engineering Design of Synchrotron Radiation Equipment and Instrumentation, Paul Scherrer Institute Villingen, Switzerland, July 2000.

[2] S. T. Smith, “Flexures, Elements of Elastic Mechanisms,” Gordon and Breach Science Publishers 2000.

[3] S. T. Smith, D. G. Chetwynd, “Foundations of Ultraprecision Mechanism Design,” Gordon and Breach Science Publishers 1992.

[4] U. Schade, A. Röser, E. H. Korte, F. Bartl, K. P. Hofmann, T. Noll, W. B. Peatman: “New infrared spectroscopy beamline at BESSY II,” Rev. Sci. Instrum. American Institute of Physics 2002.

[5] W. B. Peatman, U. Schade: “A brilliant infrared light source at BESSY,” Rev. Sci. Instrum. American Institute of Physics 2001.

[6] D. Holzweissig; “Lehrbuch der Maschinendynamik,” Fachbuchverlag Leipzig 1982, p. 135.

[7] T. Noll, "The Switching Mirror Unit for ID-Beamlines," Contribution to the MEDSI-2000 Workshop at the Swiss Light Source in Villingen/ Switzerland; July 2000.

[8] T. Noll, Th. Zeschke, G. Reichardt, H. Lammert, W. Gudat, "Six Strut Arrangements for Cartesian Movements of Mirrors," Poster auf der SRI 2000 (7th International Conference on Synchrotron Radiation Instrumentation Berlin) und Text in den Proceedings in Nuclear Instruments and Methods in Physics Research, A, Elsevier Science B. V., p. 775).

[9] Patent DE 100 42 802.5 "Vorrichtung zur mehrachsig feinjustierbaren Lagerung eines Bauteils," (Tino Noll, Heiner Lammert, Wolfgang Gudat) 20.8.2000.

[10] Registered Design DE 100 42 801.0, "Flexibles Gelenk hoher axialer Steifigkeit," BESSY (Tino Noll, Wolfgang Gudat) 2000.

[11] T. Noll, "Flexure Joints of High Axial Stiffness," Precision Engineering Elsevier Science B. V. 5298, (2002) p. 1-6.

[12] S. Zelenika, "Parasitic Motion of Cross-Spring Pivots: Theoretical Analysis and Experimental Assessment," Proceedings of the 1st International Workshop on Mechanical Engineering Design of Synchrotron Radiation Equipment and Instrumentation, Paul Scherrer Institute Villingen, Switzerland, July 2000.

[13] Aluminium alloy ACP 5080 of ALIMEX GmbH.

[14] Budik Werkzeug und Formenbau GmbH, Breitenfelde, Germany.