HIGH-PRECISION SLITS BASED ON A MONOLITHIC WEAK-LINK MECHANISM

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Abstract. *A beamline is an experimental facility that uses radiation from a synchrotron source, mainly X-rays and ultraviolet light, for research in materials, biology and nanotechnology. At LNLS (Laboratório Nacional de Luz Síncrotron), located in Campinas-SP, there are 14 beamlines installed around a synchrotron light source based on a 92-m long, 1.37 GeV electron storage ring. One of the most important components of a beamline is the slit that determines its resolution and the photon beam size. The slit aperture has to be adjustable with micrometric precision and all mechanisms have to be ultra-high vacuum compatible. The presented design is based on a stainless steel monolithic piece which contains two linked linear, orthogonal stages of compliant mechanisms built in a CF-100 double sided flange. These weak-link mechanisms are flexible structures that deliver the desired motion by undergoing elastic deformation, which leads to applications with small motion range and provides very smooth, accurate and repeatable positioning capability. A topology and shape optimization and stiffness calculation was done by finite element analysis (FEA). The flexure hinge patterns were made by wire electro-discharge machining (EDM) and provide a parallel movement of the slit's cutting faces along a 2.5 millimeter aperture range. Measurements were carried out and the results show good agreement with FEA calculations. In this paper, we describe the instrument design, prototyping, development and characterization.*

Keywords: *Beamline instrumentation, slits, weak-link mechanism, finite element analysis, mechanism design.*

1. Introduction

A synchrotron light source is composed of a particle accelerator and many beamlines. The accelerator, also known as storage ring, keeps high-energy electrons in a closed orbit (Figure 1a). The beamlines collect the full spectrum light emitted by the electrons and make it available to be used in experimental stations. The light path from the accelerator to the sample has to be done in an ultra-high-vacuum environment to avoid any intensity decrease or interference. Each beamline is a sequence of components designed to condition the light before it reaches the sample, as illustrated in Fig. 1b. This conditioning is done in order to optimize two concurrent parameters, the total flux and the resolution (Peatman, 1997). The optical instrumentation for this is based on slits, mirrors and crystals (for x-rays) or grades (for UV light) responsible for the beam size definition, focusing capacity and energy selection respectively.

The new slit design presented in this paper will be used in the D05A-TGM beamline for UV light, installed at the LNLS storage ring. It will be an entrance slit, which determines the vertical beam aperture and consequently the beamline resolution. It will be positioned approximately 8 meters from the source, where the vertical beam dimension is around 3 mm. At the ultra-high resolution beamline operating mode, the desired slit aperture is of the order of ten's of microns.

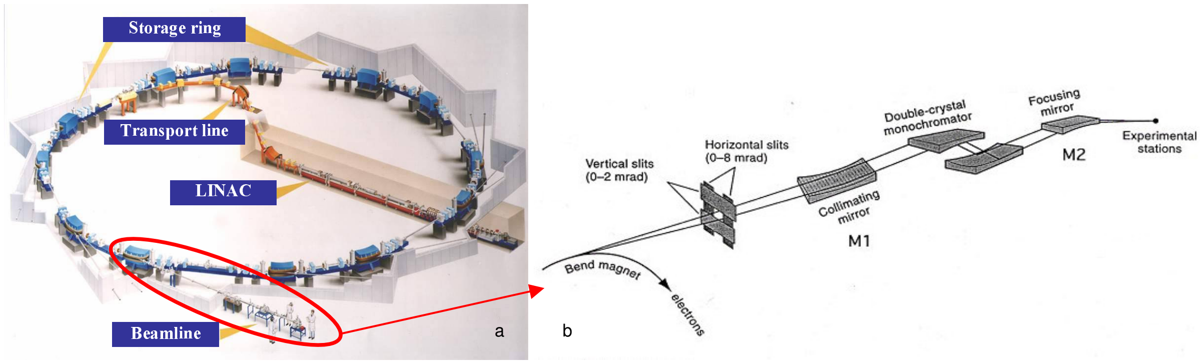

Figure 1.Synchrotron source schematical drawing (left) showing the linear accelerator (LINAC), the transport line and the storage ring where electrons are keep in a close orbit. On right, a simplify scheme of a beamline with its main optical components.

2. Proposed design

Installing a new component in existing equipment is always a challenging task. In this case, the new slit has to be short enough to minimize changes on the beamline. Also, it has to be ultra-high-vacuum compatible, which means special materials, no lubricants and capacity to support baking procedures. With respect to beamline resolution, it needs to be accurate and repeatable within few microns, especially around apertures smaller than 1mm.

We decided to use an elastic mechanism built in a special vacuum flange (Welnak *et al*, 1994). This flange has the same dimensions of a standard CF100 double sided flange, made with 17-4 PH martensitic steel instead of 316 stainless steel in order to get a better resilience.

The great advantages (National Physical Laboratory, 1956 and Shu *et al*, 2002) of this kind of mechanisms are good repeatability, no play, no axis and sleeves, no bearing or spheres, no sliding surfaces and no lubricants. Some disadvantages, as the small range of movement, are not relevant in this project.

The compliant mechanism is composed of three moving blocks interconnected by weak-links, as depicted in Fig. 2. The slit has two lips (upper and lower) screwed on vertical moving blocks. Both vertical translators are connected symmetrically to one horizontal translator trough weak-links. In this way, when the horizontal translator moves, the distance between the vertical translators, and so the lips, also change. The ratio between the horizontal movements and the slit aperture depends of the angle of the connection and it is not constant through the stroke. At this design, it was adjusted to be 1:1 at the closed position, where higher precision is required.

The function that describes the connection between the slit gap and the connection weak-link angle is defined in Eq. (1). Here, R is the size of connection weak-link and θ_0 is the angle of this link at the closed slit position.

$$\Delta(\theta) = 2R(\sin\theta - \sin\theta_0) \tag{1}$$

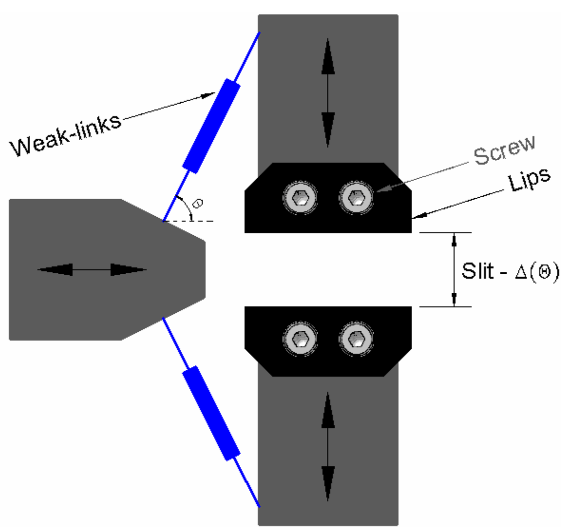

Figure 2. Compliant mechanism scheme with lips, weak-links and aperture showed. The slit gap depends on the connection weak-link angle.

A slit that works adequately has to have an essential parameter, a perfectly parallel and symmetrical aperture of the two lips.

For vertical and parallel movement a simple parallel arrangement can be used. In this configuration, see Fig. 3a, the main movement is in the vertical direction, with the lip always parallel to the horizontal, but with some horizontal displacement.

In order to have a perfectly symmetrical aperture of the two lips, the horizontal translator most not has any spurious vertical displacement. This can be reached using compound parallel arrangement, like the one illustrated at Fig. 3b. In this arrangement, the central block moves only in horizontal direction while the auxiliary frames moves in both directions.

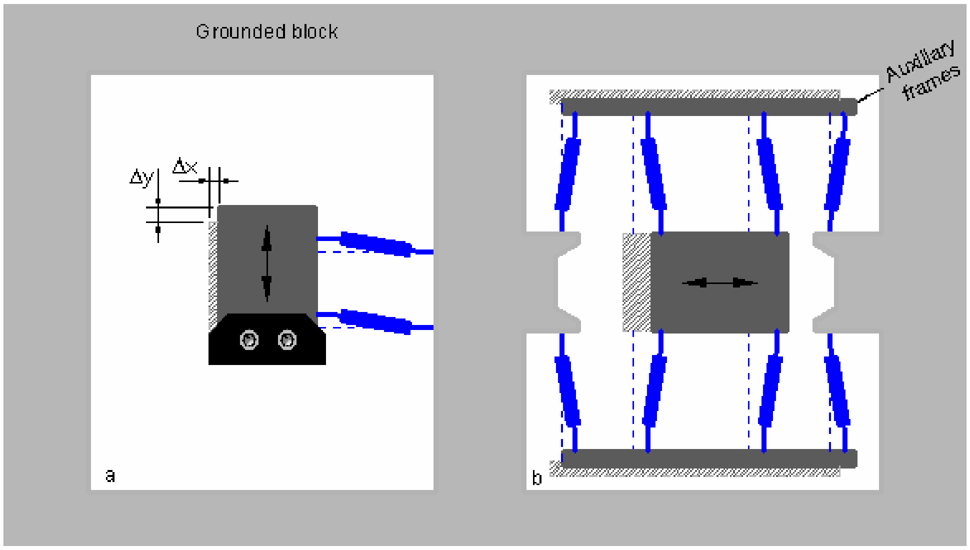

Figure 3. Two kinds of compliant arrangements. The first type presents parasitic movement Δx in horizontal direction. The type b doesn't show parasitic movement and, with same weak-link flexion, has twice the final motion range.

It was used a micrometer head to move the horizontal translator. The connection between these elements was done using a stainless steel rod, screwed in the block, and welded to a flexible bellows for vacuum sealing. A compression spring was used to push the horizontal moving block for the closed slit position, as show in Fig. 4.

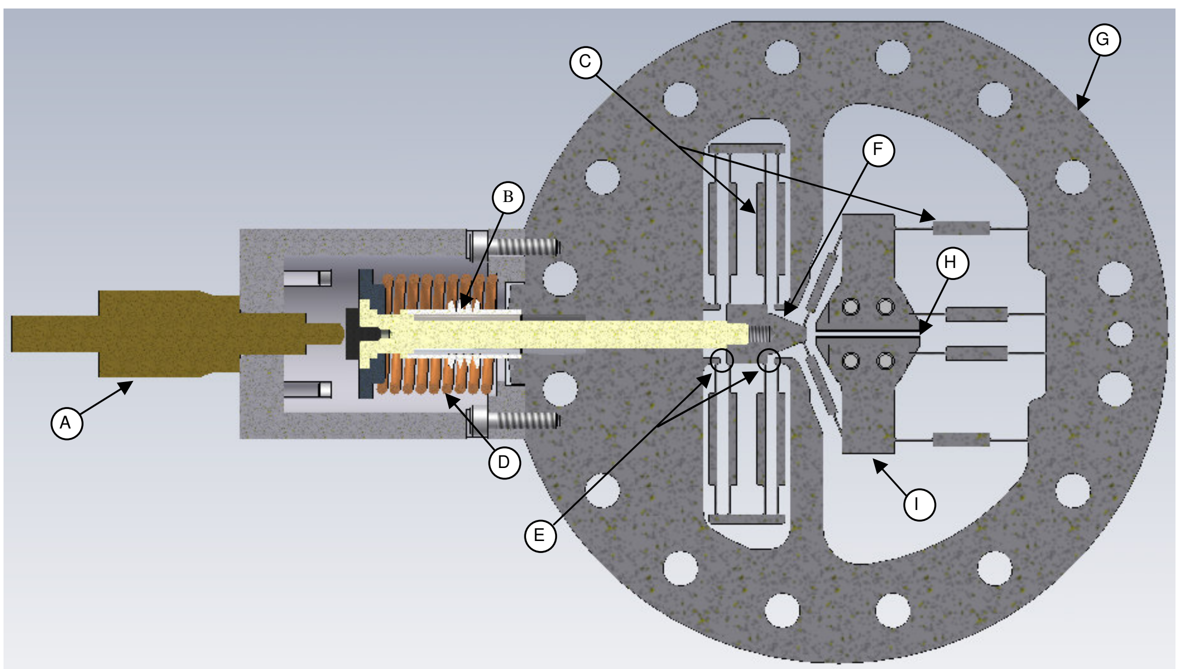

Figure 4. Full assembly of proposed design showing the micrometer head (A), sealing bellows (B), weak-links (C), return spring (D), stoppers (E), horizontal translator block (F), lips (H), vertical moving blocks (I) and CF-100 double sided flange (G).

3. Fabrication

All the moving blocks and weak-links were made by wire electro-discharge machining directly on the flange as one monolithic piece.

The flange was pre-machined with the holes used by wire EDM as starting points for material removing (Fig. 5a). The internal thread in the horizontal moving block and the threads for the lips were also produced before the electro-erosion.

An external reference surface was eroded in the same operation that the internal mechanism (Fig. 5b). It will be used to level the slit after the final assembling at the beamline. In next stage (Fig. 5c), the lips were eroded attached to the flange. With this procedure, an alignment and grinding of the light cutting faces has performed.

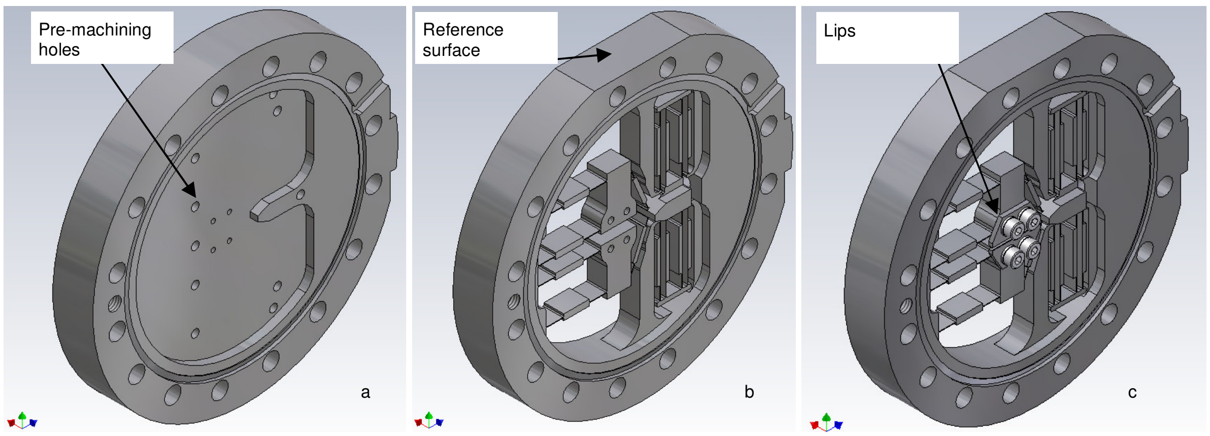

Figure 5. Three steps of compliant mechanism and slit production.

4. Finite element analysis

There were two main design parameters to be calculated by the simulations using Finite Element Analysis (FEA). The first one was the total force needed to reach the maximum slit aperture. And the other was the maximum stress in the weak-links. The first question was related with the external actuator. The force necessary to open the slit should be compatible with the actuator, in our case, a Newport® differential screw. The second question was related with the elasticity. The weak-links should work out of the region of plastic deformation.

After many simulations with different thickness of the weak-link wall, different geometries (Rodrigues, 2003), we found a model with a stiffness of 16.4N/mm and a maximum stress of 815MPa, approximately 30% smaller than the maximum for elastic deformation. The weak-link wall was ordered with a thickness of 0.25mm. Figure 6 shows the mesh used in the simulations and the final stress on the elements. Considering the symmetry plane, the simulations were done using half slit.

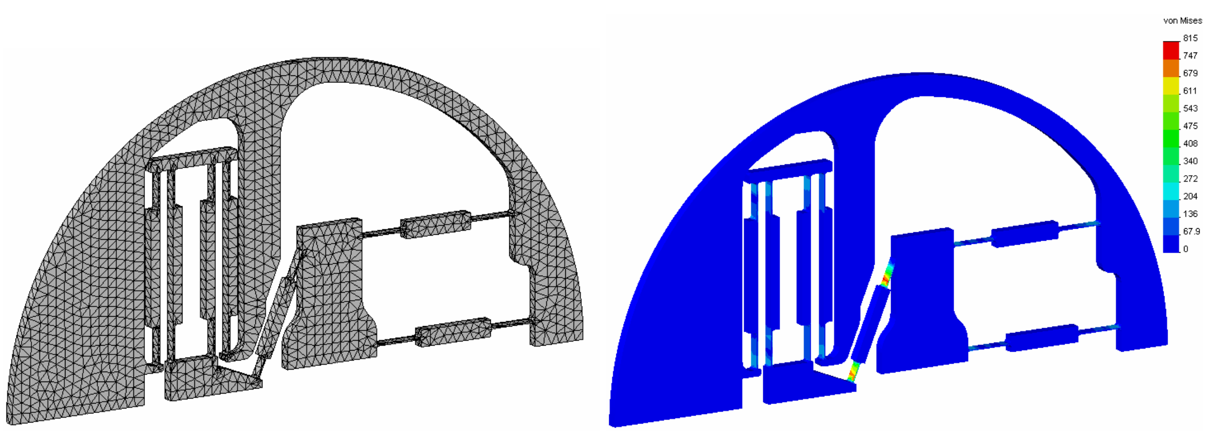

Figure 6. Used mesh in finite element simulations and the Von Misses result of the final stress analysis.

5. Results and discussions

The stiffness measurement was done by pulling the horizontal moving block and measuring its displacement with a dial test indicator. The applied force at the horizontal translator was done by blocks with known mass. The result corresponds to an elastic constant of 16.48±0.08N, in agreement with the FEA studies, as showed at Fig. 7.

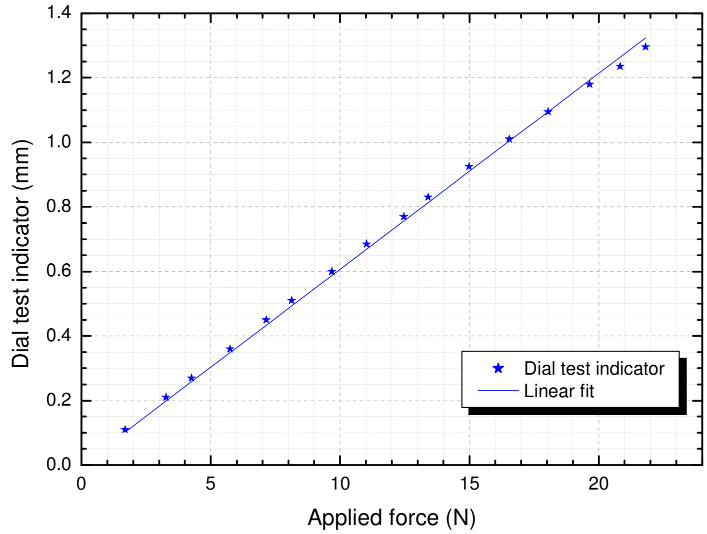

Figure 7. Data result of stiffness measurement showing that the flexible mechanism is still at linear elastic region.

The final force on the micrometer head will depend also of the return spring stiffness and the effective area of the vacuum selling bellows. Both will push the slit to closed position. The atmospheric pressure on this bellows will contribute with a force of approximately 12.23N. The test described below was carried out with a spring a little stronger to compensate the absent of vacuum pressure. In this case, with a spring constant of 3.86N/mm, the final force on the micrometer spindle varies from 5.51N at closed position to 71.02N at maximum aperture.

Using two encoders (MT25 HEIDENHAIN®, 0.1µm resolution), one gauging the horizontal moving block displacement and the other the slit aperture, we measured the slit transfer function. Figure 8 and Figure 9 show the plotted results.

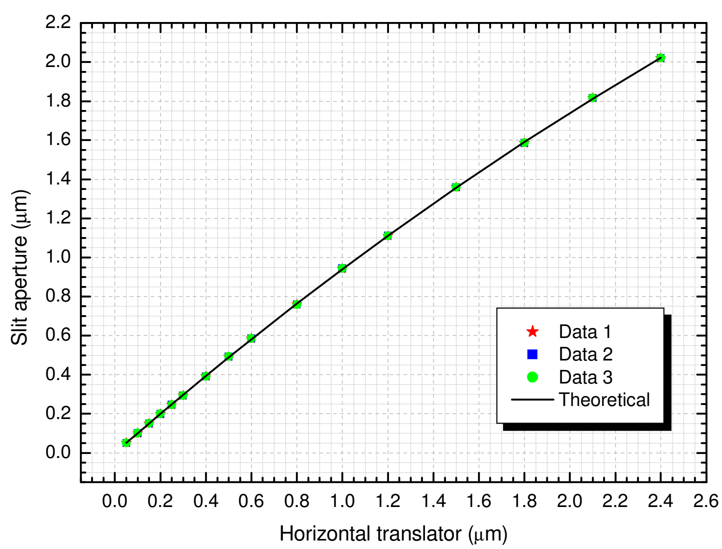

Figure 8. The measured data, slit aperture and horizontal translator and a fit of Eq. (1) to experimental data.

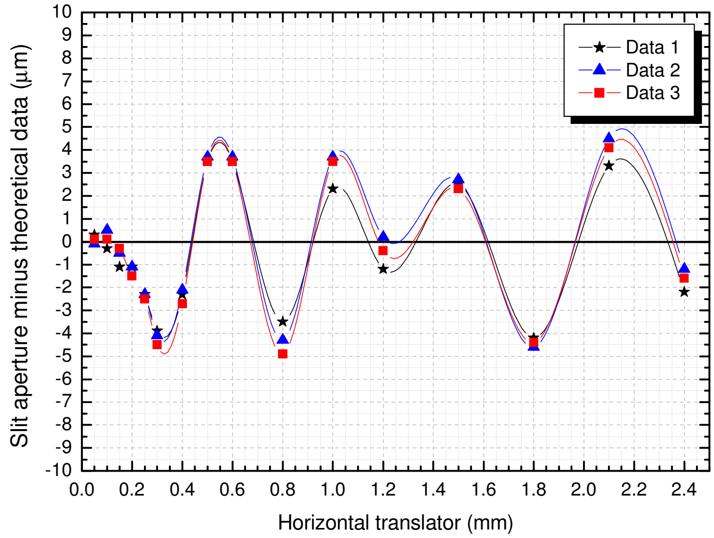

Figure 8. Calibration curve that shows the deviation of measured points from theoretical data.

The cyclic error seems to be mainly caused by the rotation spindle movement of micrometer head, since each turn correspond to 0.5mm displacement.

6. Conclusions

Compliant mechanisms are a good solution in precision instruments design. In addition, they are totally compatible with ultra-high-vacuum environment and its behavior is well predicted by finite element analysis. The proposed monolithic design spends some time in the project and analysis stages, but it is quickly and easily produced with electro erosion machine.

Although we got a slit that works linearly and with repeatability of the order of 2µm, the accuracy has to be improved.

In the next design, the contact force on the micrometer spindle will be reduced. Also, a micrometer head with non-rotating spindle will be used.

7. Acknowledgements

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8. References

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