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GRANITE BENCHES FOR SIRIUS X-RAY OPTICAL SYSTEMS

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Abstract

The first set of Sirius beamlines is expected to start operating in early 2019 and over the last few years many optical systems for the X-ray beamlines have been developed in-house at the Brazilian Synchrotron Light Laboratory (LNLS). Starting with the High-Dynamic Double Crystal Monochromator (HD-DCM), passing by the Double Channel-Cut Monochromator (4CM) and continuing with new standard mirror systems, a series of granite benches, based on high-resolution levellers, and a combination of embedded and commercial air-bearings, has been designed for high mechanical and thermal stability. Specifications, designs, and partial results are presented, showing the progressive increase in complexity according to a deterministic design approach.

INTRODUCTION

Sirius, the new Brazilian synchrotron light source, is currently under construction. As a fourth-generation machine, the synchrotron beam will have extraordinary properties in terms of size, divergence and flux. Consequently, the beamline optical elements, such as monochromators and mirror systems, must have corresponding performances to allow for proper energy selection and control of position and size of the beam at the sample, which begins with robust and stable mechanical supports (see Fig. 1).

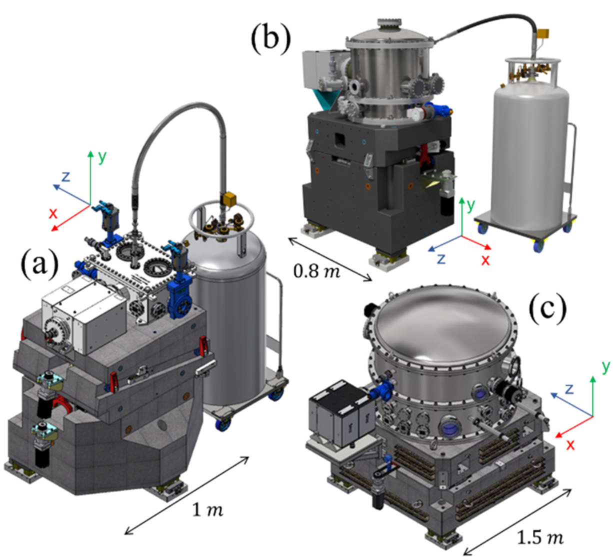


Figure 1: Optical systems mounted on granite benches: (a) mirror; (b) double channel-cut monochromator (4CM); and (c) High-Dynamic Double Crystal Monochromator (HD-DCM) (Beam direction: +z. Vertical up: +y).

Following several successful beamline instrumentation examples [1, 2], granite was chosen as the base material for the new generation of mechanical benches, due its good elastic modulus over density ratio associated to a very low coefficient of thermal expansion, since this combination results simultaneously in good thermal and mechanical performances. Moreover, to improve the stability and reduce the complexity of the assemblies of the optical elements, it was made the choice of allowing only the essential degrees of freedom (DoF) in vacuum, whereas all other DoF needed for positioning and alignment should be provided by the benches [3, 4]. In the following sections, the practical implementation of these guidelines and partial results of the benches of the High-Dynamic Double Crystal Monochromator (HD-DCM), Double Channel-Cut Monochromator (4CM) and mirror systems are presented.

CONCEPTUAL DESIGN

Since positioning the optical elements along the beam axis (*z*) does not usually have strict specifications, the granite benches have been designed to allow for positioning and alignment in the remaining 5 DoF, namely: translations, in the horizontal and vertical axes, *Tx* and *Ty*, respectively; and the associated rotations, *Rx*, *Ry* and *Rz*.

With some effort, all the most demanding specifications of different optical elements could be meet in a standard conceptual design. At the bottom level, wedge-levellers developed for Sirius girders [5] allow for Ty_1, *Rx* and *Rz*, for basic short-range height positioning and levelling. Next, functional air-bearing arrangements allow for the additional DoF by positioning different granite blocks with respect to each other. In the monochromators, *Tx* and *Ry* are implemented to overcome initial assembly and alignment limitations, and to allow for either the exchange between crystal sets (HD-DCM) or for pink beam operation (4CM). As for the mirrors, with side-bounce deflection, in addition to these two DoF, a large-range Ty_2 has been introduced to allow for the selection of stripes with different coating materials.

The choice of functional air-bearings was driven by the intention of maximizing the overall mechanical and thermal stability, and effectively optimizing the stiffness of the bench as a whole. Indeed, with this solution, it is even possible to combine different DoF over a single interface, which allows for designing the minimum number of granite parts and direct interfaces. As the air-bearings are used only during alignment, once the air is off the bench should behave nearly as an extension from the floor up to the optical elements. With conventional guiding elements, there would be more elements in the stiffness chain and particularly a significant number of interfaces, which are prone to performance limitations. Finally, combining embedded and commercial air-bearing solutions gives significant design flexibility. The first are used for lifting, so that without air there can be direct contact between the granite parts. Moreover, high determinism, particularly in terms of stiffness and stability, is obtained by building the air-bearings in specific machined areas of the granite blocks, defining contact pads with optimized geometry. In the pads, textbook grooves are added to improve the pressure distribution profile, allowing for lower operational pressure levels. As for the commercial air-bearings, they are used as guiding elements, running on internal or external tracks also directly machined in the blocks. Since each element constrains a single DoF, they can be suitably arranged to provide high-quality guiding without over-constraining limitations. Indeed, this was a key characteristic in the implementation of more than one DoF over one interface.

Figure 2 shows the granite bench for the mirror systems, with the 3 granite parts and 4 interface levels. The 1st level is between the levellers and the floor, the 2nd, between the bottom granite and levellers, the 3rd and 4th, between the granite parts. In the 3rd level *Tx* and *Ry* are implemented together, whereas the combined translations of the 3rd and 4th levels provide *Ty* in a wedge-type solution, similar to that adopted in the APS Velociprobe [2]. Comparing the two wedge solutions, here the wedge angle was increased from 7.5° to 8.5° to reduce strokes, while keeping self-locking with a safety factor of 2.8, and a vertical guide was not compatible with the design of only 3 granite parts for all the DoF.

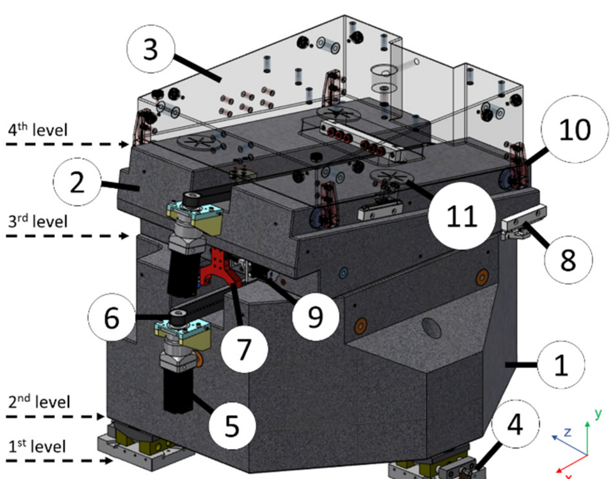
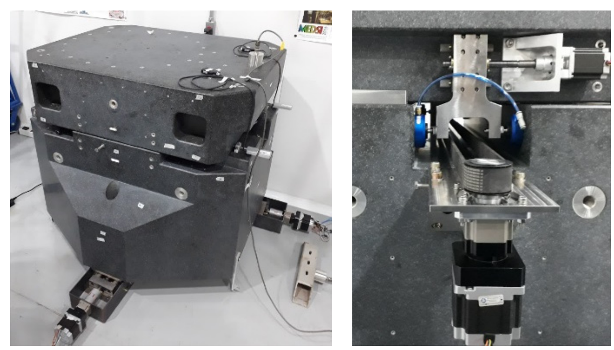


Figure 2: Three-part granite bench for the mirrors systems: (1) bottom granite; (2) middle granite; (3) top granite (transparent for visibility); (4) wedge-leveller; (5) stepper motor for *Tx*; (6) timing belt for *Tx*; (7) commercial air-bearing guiding for *Tx*; (8) optical encoder; (9) power screw mechanism for *Ry*; (10) commercial air-bearing for wedge; and (11) machined air-bearing pad.

All mechanisms are driven by stepper motors, which are connected either to power screws, for the levellers and the *Ry* solution, or to timing belts, for the translations between granites. The latter option also prevents over-constraining issues, not only allowing for the integration of *Tx* and *Ry* in a single level in the first place, but also relaxing eventual alignment problems that might occur between power screws and the air-bearing guides. For feedback and metrology, all five DoF plus the additional *Ty* are covered by: three length gauges installed between the bottom granite and the floor; and three Renishaw REVOLUTE absolute encoders with 0.5 µm resolution, which are particularly useful to comply with the *Ry* DoF for having large yaw misalignments tolerances.

RESULTS AND DISCUSSION

The granite bench of HD-DCM was assembled and functionally validated in the second semester of 2017, building up confidence in the proposed approach and unlocking the design of the benches for other optical components. Next in line were the 4CM and the mirrors, with progressive complexity levels. The components for the mirror benches are still in manufacturing phase, but most of the parts of 4CM bench have already been delivered, which allowed for a new round of experimental analyses for motion and dynamic performances. Figure 3 shows this assembly at the hall of the metrology building at LNLS:



(a) (b)

Figure 3: (a) 4CM granite bench assembled at the hall of the metrology building of LNLS; (b) Detail of *Tx* and *Ry* stepper-driven actuation mechanisms with the timing belt and power screw, guided by the commercial air pad.

Dynamic Analysis

The most stringent mechanical RMS stability specifications in the optical systems are in the order of 1 μm for translations and 50 nrad for rotations. Extracting meaningful absolute stability data of systems out of their final destinations and operational conditions, however, can be fairly difficult, because a significant part of it is a response to cultural noise. Nevertheless, to get some reference numbers, a few measurements for the integrated RMS values between 1 and 450 Hz were recently made using Wilcoxon 731A accelerometers. As a result, numbers below 40 nm and 30 nrad for the HD-DCM on a special floor of the metrology building were achieved, whereas up to 200 nm and 100 nrad were found for the 4CM in the common floor of the hall, close to the HVAC system. Sirius experimental floor is built for exceptional performance, so that, even with its cultural noise, the specs are expected to be met.

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Moreover, regarding the conceptual design choices, investigations of modal analyses bring important information. In that sense a toolbox developed in Matlab to build 3D mode shapes from experimental data has proven to be extremely useful. Figure 4 shows de frequency response functions (FRF) built with signals of a Kistler 8726A accelerometer and a PCB Electronics hammer for about 25 points of interest over the complete structure. It can be seen that below 40 Hz the coherence is very level low, so that no meaningful information can be extracted. To improve the signal quality in this frequency range, measurements with a shaker are most likely needed and may actually provide relevant transmissibility information. Indeed, up to this frequency the bench and the floor are coupled, so that it is difficult to achieve good signal to noise ratio. Then, at about 45 Hz, matching very well with expected values from simulations, the first rigid body modes (*Rx* and *Rz*) appear for the whole structure and the signals generally improve. Adding a preload of 20 kN per leveller, which is equivalent to increase the preload given by weight alone by a factor 3, only caused a shift of about 4 Hz in frequency, suggesting that the stiffness link between the bench and the floor is close a practical limit within the present concept. Indeed, since the stiffness of the floor itself may be a limitation, having peaks at relatively low frequencies becomes an inevitable drawback of using such heavy granite benches. Although larger floor stiffness can be expected in Sirius experimental floor, it is arguable how much improvement can be obtained frequency-wise. Nonetheless, if needed, passive damping solutions may be introduced to keep displacements down to the nm level. Yet, knowing that the 120 and 175 Hz peaks are also related to rigid body modes, it can be seen that the first modes between granites occur above 450 Hz, which validates the design choices with the intention of creating nearly monolithic structures.

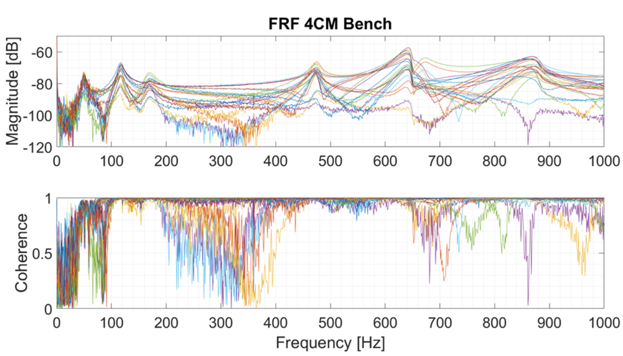

Figure 4: Frequency response function used for experimental modal analyses in the granite bench of the 4CM.

Motion Analyses

Based on the alignment and performance requirements of all the optical systems currently under design or manufacture, a set of standard specifications was defined for the benches, including: accuracy, range, resolution, repeatability, and stability. For the optical elements, accuracy is essentially defined by proper alignment with respect to the beam, so that it can be encompassed by sufficient range and resolution. In terms of range, there were practical limitations because of design choices, but not risks. Resolution, on the other hand, tends to be dominated by friction, requiring more careful investigation. If metrology is present, in simple systems the repeatability also becomes a function of resolution, provided that the target position may be achieved within a reasonable number of iterations.

Table 1 summarizes the motion specs and the results for the DoF available in the 4CM bench. Since not all electronic parts were yet available, the motion characterization was carried with Heidenhain's MT25 length gauges, with accuracy below of 0.5 μm. It can be seen that the only item that fell out of specs was the translation *Tx*, which was off by a factor 10. This is related to the compliance of the timing belt and to the creation and removal of the air film. This result must be rechecked with realistic preload, as expected at the beamlines due to bellows and vacuum forces. Else, the driving reasons of this spec may be reviewed or reconsidered. Yet, the tight resolutions of 1 μrad in the levellers, which were of concern, could be successfully met, even with extra preload.

Table 1: Summarized Specifications for Mirrors and Monochromators Granite Benches and Results for the 4CM

Axis	**Range** [mm/mrad]		**Resolution** [µm/µrad]	
	Spec	**Exp.**	**Spec**	**Exp.**
Tx*	–	± 9	0.5	5.3
Ty_1	± 2.3	± 2.3	1	0.5
Ty_2**	± 10	–	1	–
Rx	± 3.5	± 5	1	0.8
Ry	± 10	± 11.5	1	1
Rz	± 3.5	± 5	1	1

* Range very much dependent on the system.
** For mirror systems only.

CONCLUSION

Deterministic design concepts have been applied in the development of high-stability granite benches for Sirius X-ray optical elements. Experimental analyses of a monochromator bench proved that the innovative functional air-bearing solutions allowed for the realization of robust structures, with internal eigenfrequencies above 450 Hz, yet providing fine motion resolution which approach the sub-micrometer and sub-microradian ranges. The evaluation of the mirror benches and further investigations about stability levels, transmissibility and damping are expected in the near future.

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