THE NEW HIGH DYNAMICS DCM FOR SIRIUS

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Abstract

The monochromator is known to be one of the most critical optical elements of a synchrotron beamline, since it directly affects the beam quality with respect to energy and position. Naturally, the new 4th generation machines, with emittances in the range of order of 100 pm rad, require even higher stability performances, in spite of the still conflicting factors such as high power loads, power load variation, and vibration sources. A new high-dynamics DCM (Double Crystal Monochromator) is under development at the Brazilian Synchrotron Light Laboratory for the future X-ray undulator and superbend beamlines of Sirius, the new Brazilian 4th generation synchrotron [1]. Aiming at an inter-crystal stability of a few tens of nrad (even during the Bragg angle motion for flyscans) and considering the limitations of the current DCM implementations, several aspects of the DCM engineering are being revisited. In order to achieve a highly repeatable dynamic system, with a servocontrol bandwidth in the range of 200 Hz to 300 Hz, solutions are proposed for a few topics, including: actuators and guides, metrology and feedback, LN2 indirect cooling, crystal clamping, thermal management and shielding. The concept of this high-dynamics DCM will be presented.

INTRODUCTION

In the recent years it has become clear to the synchrotron community that the stability performance of DCMs would turn out to be one of the main bottlenecks in the overall performance of many X-rays beamlines, particularly for the new generation of machines, the so called Diffraction Limit Storage Rings (DLSR). This is because the instabilities in the DCM affect the position and/or the effective size of the virtual source, and, consequently, the spot size and/or the position of the beam at the sample. It is thus imperative that the virtual source instability is kept within a small fraction of the source size. The angular instability between the two crystals is the most critical one because its effects on the virtual source scales with the lever-arm between the monochromator and the source (L_0 in Fig. 1). In the DLSR, the sources are expected to have only a few microns, whereas the typical distances between the source and the monochromator is of tens of meters. Due to that, the stability between crystals is required to be within a few nrad. This scenario has motivated numerous special forums in conferences and even dedicated workshops, as the *ESRF DCM Workshop* in 2014. Since then, an effort has been made by suppliers and the synchrotron engineering community, trying to upgrade the existing systems and come up with new solutions. This work, which is the outcome of such effort at the Brazilian Synchrotron for Sirius beamlines, presents the advanced conceptual design of a DCM with high servo bandwidth closed-loop control. Sirius is in construction phase and the beginning of machine commissioning is planned for mid-2018 [2]. Therefore, a functioning prototype of the DCM has been planned for mid-2017.

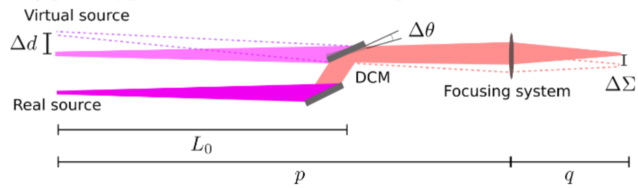

Figure 1: Effects of DCM instabilities in the virtual source.

STATE OF THE ART

Many of the existing DCMs around the world have been recently characterized with respect to stability. Representative cases were shown at the ESRF DCM Workshop, as the one by Ilya Sergeev, in which none of Petra III and ESRF DCMs performed below 100 $\mathrm{nrad_{RMS}}$ [3]. Table 1 shows some of the most recent results of one of the state-of-the-art commercial DCMs [4]. The absolute pitch tells the angular instability of the second crystal, whereas the relative pitch shows the instability between the two crystals. The latter not only may affect the monochromatic beam with respect to flux, depending on the energy selection characteristics of the crystals, but, as mentioned, certainly affects the virtual source size and/or position, depending on the acquisition rate and sampling time of the experiments.

Table 1: Pitch Vibrations of State-of-the-Art DCM in the Range between 0 to 2.5 kHz (as reported in [4])

Experimental Condition	RMS (nrad)
Absolute pitch with servoing Bragg	278
Absolute pitch w/ braked Bragg	92
Relative pitch with servoing Bragg	100
Relative pitch w/ braked Bragg	48

From Table 1, it can be seen that this instrument performs around 50 nrad for the braked rotary stage. However, even this lowest value is still too high for the recent and future specs. In addition, given the fast development of detectors and electronics, there has been a lot interest in flyscan experiments, which requires high stability levels to be kept not only with the servoing Bragg, but in actual motion.

SPECIFICATIONS

The project of the DCM at LNLS has started with the case of a beamline with a planar x-ray undulator as the radiation source. Having the DCM at the distance of about 30 m from the source, Fig. 2 shows the variation of the position of the virtual source as a function of the variation of

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the angle between the crystals, and correlates that with 10% of the vertical and horizontal size of the source. It shows that only about 10 nrad instability would be allowed to keep the displacement of the virtual source below 10% of its size. And, of course, this number is further reduced for more conservative targets. Table 2 summarizes the main functional targets of this DCM.

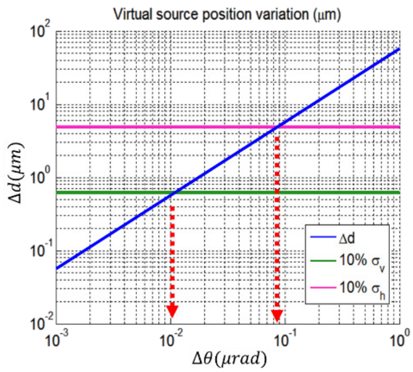

Figure 2: Variation of the position of the virtual source as a function of the variation of the angle between the crystals for the DCM at 30 m from the source.

Table 2: Main Functional Specs for the DCM Prototype

Parameter	Description
Type:	Vertical DCM
Beam offset:	18 mm
Angular range:	3 to 60°
Angular resolution:	0.2 μrad
Pitch/roll stability:	in-position: < **10 nrad** ($\pm 3\sigma$) flyscan: < 200 nrad ($\pm 3\sigma$)
Crystal sets:	Si(111): 2.3 to 38 keV Si(311): 4.4 to 72 keV
Crystal sizes (*W*x*L*):	1st crystal: 15 x 35 mm^2 2nd crystal: 15 x 190 mm^2
Crystal cooling:	1st crystal: Indirect LN_2 (80 K) 2nd crystal: Copper straps (155 K)
Crystal DoF:	1st crystal: fixed at the rotation axis 2nd crystal: gap, pitch, roll
Beam size:	1.7 x 1.7 mm^2
Input Power:	150 W
Base pressure:	< 5 x 10^{-8} mbar

Concerning in-position stability, the specified level must be improved by a factor between 10 and 100 with respect to existing systems (also note the $\pm 3\sigma$ spec as opposed to RMS values in the reference). As for the stability performance during flyscans, similar dedicated evaluation of operating DCMs is unknown to the best of our knowledge. Achieving this large improvement seemed hardly possible by incremental upgrades, thus, a complete revaluation of the DCM as a system has been made. A few concepts have been borrowed from proven technologies in high-end machines of the semiconducting industry and a systematic review of the traditional solutions has been performed.

CONCEPTUAL DESIGN

Guidelines

The first rule in this development was to restrict the number of degrees of freedom (DoF). Therefore, the crystal cage presents only pitch, roll and gap adjustments, and all of them are associated to the 2nd crystal subsystem. The more degrees of freedom, the harder to keep the stiffness and robustness of the system, and the more error sources.

Next, it was believed that the required stability numbers could not be achieved without a high bandwidth closed-loop servo control, through which disturbances can be attenuated to acceptable levels. In this DCM the target is a closed-loop control bandwidth of at least 200 Hz, for which force actuators and a reaction mass are used for pitch, roll and gap adjustments.

This high controllability of the system also imposes strict requirements on the feedback system, particularly on resolution, stability and acquisition rates. With respect to that, some uncertainty lies on what can be available at the beamlines: intensity monitors may not be sensitive enough for nrad variation; beam position monitors (BPMs) may not be sensitive, accurate and/or fast enough (kHz range); due to the high coherence properties of the new machines, some beamlines may not accept any interference of windows or foils in the be beam path. Thus, the DCM has its own internal metrology system for servo feedback to control the gap, pitch and roll between the crystals with the former mentioned high closed-loop bandwidth. High stability and resolution is obtained by using distance measurement interferometers (DMIs) and mechanical components designed to reach high-stability and eigenfrequencies.

Finally, the cooling induced vibrations have been considered as the main risk item, so that alternatives to the cooling technology have been investigated, in order to minimize disturbances and mechanical constrains.

Design

The DCM can be divided in the following parts: support, vacuum vessel, rotary system and core (Fig. 3). The support is responsible for positioning and aligning the system at the beamline and is composed by two thick granite stones stacked upon each other and a few adjustment mechanisms. The bottom granite lays on manual or motorized levellers, that should provide the appropriate level (Rx and Rz) and height (y) to the system. The top granite allows for manual adjustment of the remaining rotation (Ry) and motorized lateral shift (x), which also provides the selection of the crystal set. For this translation, rather than conventional linear guides, customized high-stiffness pads are being designed. The necessity to apply additional damping (with high damping polymer) in the support will be investigated in the next phase. This may elegantly combine non-overconstrained supporting in the low-frequency range (related to mounting and thermal drift) and overconstrained design, with high stiffness, in the high-frequency range (associated with support eigenfrequencies).

The bottom flange of the vacuum vessel is directly glued to the top granite (or bolted from below in a matrix pattern), so that the flange takes advantage of the full stiffness of the granite. Then, the in-vacuum rotary system is directly mounted on the bottom flange. The choice in favour of an in-vacuum solution lies in the attempt to improve the mounting stiffness of the core and prevent it from the vibrations that can be associated with the vessel. Stiffness is improved by means of bearings at both sides of the main rotating frame (GOF). For now, there is an active bearing with a direct-drive actuator at one side and a passive bearing at the other, however, in the future two active bearings may be implemented for superior control. Both bearings have flexural decoupling fixtures in order to prevent over-constrained design, so that each bearing defines a rotation point and the actual rotation axis is defined by the complete set.

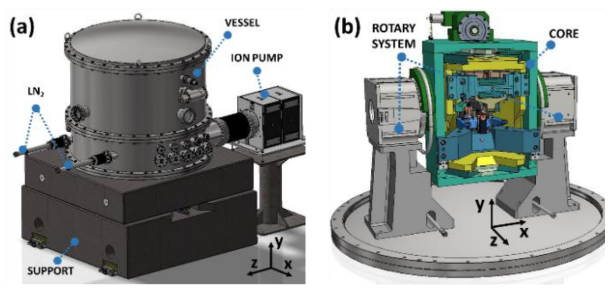

Figure 3: DCM assembly: (a) Overall view. (b) Downstream internal view of the rotary system and the core.

As for the core, the detailed design is shown in Fig. 4. By design the diffracting surface of the 1st crystal (CRYS1) is in the rotation axis of the rotary system, which, being at the beam height, prevents the beam from walking across the first crystal. This maintains the heat extraction as effective and well balanced as possible, and prevents transient effects in the lattice distortion due to the local thermal expansion. CRYS1 is manufactured in T-shape and directly clamped to a metrology frame (MF1) via calibrated pads that can correct coarse miscut errors of the crystals. This correction allows for substantial reduction of the required angular stroke for pitch and roll tuning and also minimizes misalignment metrology errors. In order to limit stress and strain in the crystals due to thermal expansion mismatch with respect to the frame, flexural elements are machined in MF1 around the three fixation points of each crystal. Even so, the eigen modes in the assembly are still made above 1 kHz. These flexures also act as high thermal resistance that help the overall thermal management. The same fixation concept is applied to the 2nd crystals (CRYS2) and their metrology frame (MF2). MF1 holds three mirrors (IFM) and MF2, three heads (IFH) of the DMIs. IFM alignment is guaranteed by machining tolerances, whereas IFH has a submilliradian alignment fixture (IFAM).

MF1 is mounted on an intermediate frame (YFM), which is then mounted to GOF. The LN_2 manifold (CMF), from which the cooling pipes are derived to the copper blocks (CB1), is also fixed to YFM. As commonly done, indium foils are used between CRYS1 and CB1 to improve the lateral cooling thermal contact between and reduce clamping distortions in CRYS1. The pipes are designed so that their stiffness does not compete with the mounting stiffness between CRYS1 and MF1. Inside CB1, channels in a coil profile maintain the dimensions of the tubes, so that the flow can be kept with minimum variation. The small channels also help increasing the effective heat transfer area between the fluid and CB1, allowing for smaller flows, which should lead to smaller vibration levels. They are machined in separate parts that are afterwards brazed together. More details about the dedicated flow-induced vibration studies are found in [5].

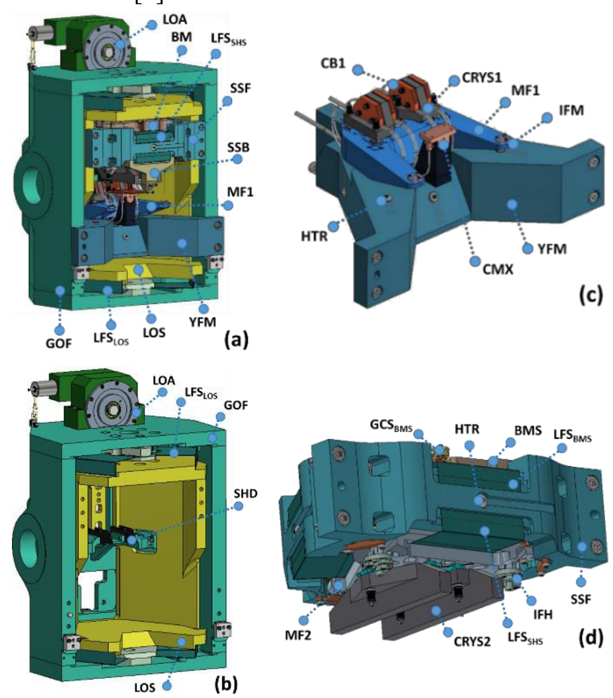

Figure 4: Mechanical design of the core of the DCM: (a) Complete set; (b) Long-stroke module; (c) 1st crystal module; (d) 2nd crystal module. (Acronyms in the text.)

From CMF, an extension is derived (CMX) and serves as the heat sink for CRYS2, so that it can be indirectly cooled through an association of copper straps (HCS and CCS). This indirect cooling solution for CRYS2 prevents flow-induced vibrations and is feasible since they were conveniently specified to work at 155 K. Indeed, as the temperature of the hot spot of the 1st crystal is expected to vary between 77 and 130 K during operation, depending on the total power and power density absorbed (related to the *K*-value of the undulator and the beam footprint, respectively), any attempt to match the lattice parameters of both crystals is quite discouraging. Thus, as it can be seen in Fig. 5, if CRYS2 is stabilized at 155 K, it is half-way the maximum pitch mismatch due to thermal expansion effects, i.e, about 30 µrad at about 130 K with respect to 77 K. In this case, the pitch tuning range that is required to maximize flux can be minimized, only $\pm$15 µrad, as well as the gap adjustment to eventually compensate for beam position variations at any given element downstream the DCM caused by this missteering.

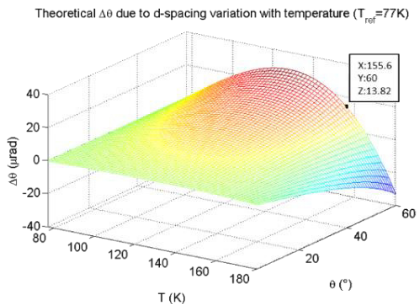

Figure 5: Pitch compensation for perfect energy matching as a function of temperature and angle.

To the best of our knowledge, the main innovation in this project is in the way the DoFs of CRYS2 are guided, actuated and controlled [6]. Firstly, all the guiding is performed by folded leaf-springs. By this choice, lubrication, friction effects and vibrations from recirculating spheres or rollers can be mostly eliminated. These factors allow for more deterministic design, and motions with higher resolution and repeatability and less noise. In addition, all the 3 actively controlled DoFs, namely, gap, pitch and roll, can be implemented for MF2 in a single stage, by the composition of 3 folded leaf-springs (LFS_{SHS}). Yet, since the elastic elements of the guiding have limited working range (and the actuator, limited range/resolution), one complementary translation module, guided by 6 folded leaf springs (LFS_{LOS}), is included. As a matter of fact, 5 folded leaf springs suffices to constrain the necessary DoF for this translation, but the 6th will improve symmetry and stiffness of the assembly.

In regular operation, this long stroke frame LOF may travel over $\pm$2.75 mm with respect to GOF, whereas MF2 may travel over $\pm$1.75 mm and rotate by $\pm$1 mrad in pitch and roll with respect to LOF, so that the 9 mm gap requirement and the angular tuning can be performed. The actuation at the LOS is performed by a servomotor and a cam in a stiff mechanism (LOA), which is fixed to the GOF and has the necessary decoupling design to match with the 6-folded-leaf-spring guide. The actuation of MF2, on the other hand, is provided by three voice-coils actuators (VCA) that act against a reaction mass (or balance mass, BMS), instead of acting against the main structure, as ordinarily done. Just as MF2, BMS is also guided by 3 folded leaf-springs (LFS_{BMS}) and has the same 3 DoF with respect to LOS. Then, as the inherently compliant force actuators allow MF2 and BMS to be decoupled from each other, and both of them decouple from the LOS at about 7 Hz, superior dynamics can be achieved in the system, thanks to filtering effects. Figure 6 shows the schematic drawing of this high-dynamics module, whereas the detailed discussion of the mechatronics concepts is found in [7].

In order to simplify assembly and alignment procedures, MF2 and BMS are not directly mount to LOS via LFS_{SHS} and LFS_{BMS}, but to an auxiliary frame (SSF), which is then stiffly mounted to LOS. Moreover, in order to minimize actuation effort, both MF2 and BMS have the same decoupling frequencies, so that the gravity sag effects are similar to both of them. Additional springs are used as gravity compensators (GCS_{SHS} and GCS_{BMS}), which can be adjusted during assembly to achieve the required positioning alignment. Studies and simulations of stresses in the leaf springs, parasitic motion and alignment have been extensively performed to guarantee that the proposed solution is feasible. Also, several hard end-of-stroke features will assure safe conditions.

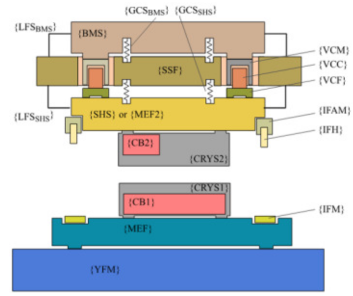

Figure 6: Schematic drawing for the 1st and 2nd crystals submodules in the crystal cage, according to the high-dynamics concepts. (Acronyms in the text.)

VCA is composed of the magnet assembly (VCM) and coil assembly (VCC). The first is directly fixed to BMS and the latter, via an auxiliary fixture (VCF), to MF2. VCF is a thermal barrier between MF2, at -60°C, and VCC, which is required to be above -30°C. This condition should be assured by auxiliary copper straps connecting VCF and SSF, which will have an active temperature control set to room temperature. Besides SSF, CRYS2 and YMF are the two other parts that also have heaters (HTR) for temperature control, at 155 K and room temperature, respectively. More details regarding the thermal management in the DCM are found in [7].

As for shielding, the present design allows the most convenient shielding structure (SHD) to be directly fixed to GOF, so that its negative effect on stability can be virtually eliminated. It is well known that many DCMs suffered from resonances in their shielding structure.

Finally, DMIs seem to be the most suitable option for metrology and feedback in this application, given the working distance constrains, the measurement stroke of several millimeters and nanometric requirements for resolution, accuracy and stability. Fortunately, a few attractive commercial options have been released in the last years, as they are compact and may be specified for vacuum compatibility and radiation hardness. Therefore, the metrology is made by a set of three fiber optics distance measurement interferometers (either Michelson or Fabry-Perot interferometers), having IFM fixed to MF1 and the IFH to MF2, as already mentioned. The 3 measurement axes provide feedback for gap, pitch and roll with a sampling rate of 10 kHz, necessary to achieve 200 to 300 Hz servo bandwidth.

Control

The control system must not only internally manage the DCM system, while maintaining the parallelism between the crystals within the specified 10 nrad stability, but synchronize it with external signals. Internally, there are two very different control level requirements, namely, the energy selection, and the fine gap and parallelism. The first is responsible for controlling GOF (Bragg angle), as well as the correlated LOS, with respect to their optical encoders and with closed-loop bandwidth of 35 Hz and 20 Hz, respectively; the latter is the main feedback loop, with closed-loop bandwidth above 200 Hz, which controls MF2 with respect to the readings of the interferometers. Concerning external references, the undulator can be used as a master to the energy loop, whereas beam position monitors (BPMs) and/or other instruments at the beamline may be used as auxiliary reference inputs to the high-dynamics loop.

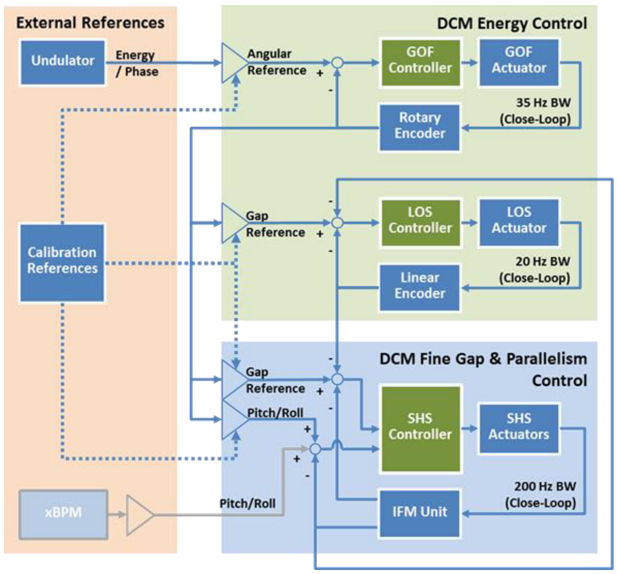

Figure 7: Control system diagram.

Table 3: Main Control Specifications

	GOF	LOS	SHS	Therm.
Actuator Type	Torque Motor	Servo	Voice-Coils	Foil Heaters
Sensor Type	Rotary Encoder	Linear Encoder	IFM	NTC RTDs
Res.	<50nrad	<0.1µm	<0.5nm <5nrad	<10mK
Closed-Loop BW	35 Hz	20 Hz	>200 Hz	0.1 Hz
Feedback Sampling	10 kHz	10 kHz	10 kHz	20 Hz

A diagram of the proposed control system is depicted in Fig. 7. Finally, Table 3 shows some specifications of actuators and sensors, including information regarding the temperature control, in order to minimize alignment and metrology errors.

Calibration and System Characterization

It is known that the parasitic motion of the leaf-springs, particularly the variation that occurs due to the rotation of the system with respect to gravity, and the power load variation, due to the variation of the parameters of the undulator, will require the DCM to be calibrated. Thus, from start the design rule has been to make the system based on high repeatability principles, so that high quality calibration should be possible. We expect that this calibration will be exclusively a function of the Bragg angle. This will be important when additional external feedback is not available during experiments.

Indeed, not all the quantitative data that was desired and/or required in the design phase was available in the literature or by experience. Thus, parallel projects have been carried out, such as the one about flow-induced vibrations [5], and the best efforts have been made in estimating the missing values, such as scattered power in critical components and black-body radiation [8]. Yet, whenever possible, a more conservative design approach has been applied in order to guarantee a functional performance. Nevertheless, the rich sensing architecture and the high controllability of the system should allow for instructive system characterization during commissioning phase.

CONCLUSIONS

The high-dynamics concepts that are applied here are proven technologies in high-end lithography machines, meaning that, although there is some innovation within the synchrotron instrumentation community, it comes under calculated risks, based on extensive and continuously updated analyses and predictive modelling. Thus, based on a consistent approach, the high-stability target has been confidently pursed and a functioning prototype should be ready for commissioning in mid-2017.

Lastly, it is worth mentioning that, regarding motion control and metrology for beamline instrumentation, this project has spawned new engineering concepts for other opto-mechanical devices of 4th generation synchrotron that has reflected in the design of several other mechanisms of the Sirius beamlines, including mirror systems and sample stages.

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