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Nanomotion for ALBA II: laboratory, metrology and control for precision engineering

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Abstract
The ALBA synchrotron facility, located near Barcelona, is undergoing an upgrade to ALBA II, a fourth-generation machine that will deliver lower emittance and higher brilliance beams. These improvements introduce stringent requirements for motion control, metrology, and synchronization across beamline instrumentation. To address these challenges, ALBA has established the Nanomotion Laboratory, a dedicated space for precision engineering research and development. The laboratory combines ultra-stable infrastructure with cleanroom environments and advanced metrology capabilities to support both beamline services and exploratory projects. Current activities include interferometer-based feedback for optical components, FPGA-driven synchronization for high-speed experiments, runout metrology and correction, and the development of ptychography scanning systems. This paper presents the laboratory's facilities, ongoing projects, and performance targets, aiming to foster collaboration with the broader precision engineering community.

Precision motion control, nanometrology, synchrotron instrumentation

1. Introduction

ALBA is the 3rd generation syncrothron facility located near Barcelona, Spain; currently working on the design of its upgrade to a 4th generation machine, ALBA II.[1] This upgrade will deliver a lower emittance and a higher-brilliance beam, enhancing the resolution and coherence available at the beamlines. These exceptional properties introduce new challenges in precise motion control and equipment synchronization to fully exploit their potential. To address these challenges, alongside the first designs, prototypes, and tests, ALBA has built and recently inaugurated a new Nanomotion Laboratory.

The Nanomotion Laboratory will tackle the aforementioned challenges. Over the coming years, until ALBA II delivers its first beam (currently expected in 2032), the laboratory will test different precision components and designs to support developments carried out by the engineering, electronics, and controls teams. In general terms, the work will focus on applying mechatronics to the current workflow.

This paper introduces the laboratory to the broader precision engineering community, aiming to establish new collaborations with a wider network beyond the synchrotron environment.

2. Laboratory spaces

The laboratory is located in the nominal position of beamline BL17 at ALBA, which would otherwise remain unused due to its short length. This location allows the laboratory to be built on top of ALBA's main slab, which is isolated from the ground. As a result, the laboratory shares similar conditions to those present at the beamlines, with overall improved stability.

See Figure 1 for an overview of the different parts of the laboratory, detailed next.

The main space of the laboratory is constructed as a cleanroom (ISO 2–3 without personnel, ISO 6–7 with personnel). It includes three PC workstations, two optical tables, and a floor plate embedded in the ground. The environment inside is constantly monitored to provide reproducible conditions between tests. The established work procedures use feedthroughs and patch panels connected to racks outside the lab, avoiding the introduction of electronic equipment inside whenever possible to maintain room stability.

If large equipment needs to be introduced into the cleanroom, a set of large double doors provides direct access to ALBA's Experimental Hall. In addition, the ceiling above the floor-embedded plate is removable, allowing the use of the Hall's main cranes.

A smaller room inside the clean room is reserved for the most demanding work. Its main characteristic is the absence of lighting and air conditioning. This passive room is located adjacent to the concrete accelerator tunnel on two walls, with air gaps to the main clean room on the other two walls and the ceiling. The result is an extra level of stability compared to the main room. This space contains an optical bench as a workspace, a patch panel connected to the outside, and a feedthrough on one wall to keep heat-generating electronic equipment outside in the clean room when short cabling is to be used.

The last room of the laboratory is a control room, which includes the dressing area for the cleanroom as well as workstations to control operations inside.

In Figure 2, the monitoring panel displayed in the control room is shown. It presents data from the environmental sensors installed in the laboratory and allows historical review for all of them. Altogether, over two weeks of normal working conditions, the main room maintained a controlled relative humidity of 44 ± 2 %, an overpressure relative to the Experimental Hall of 0.24 ± 0.01 mbar, and a temperature of 22.89 ± 0.03 °C. The super-quiet room maintained a temperature of 23.02 ± 0.01 °C.

3. Ongoing projects

The laboratory operates on two fronts for ALBA. On one side, it provides services to the beamlines. This includes external metrology—performing measurements of motion components before installation to ensure that requested specifications are met—as well as collaborating with other ALBA teams on designs

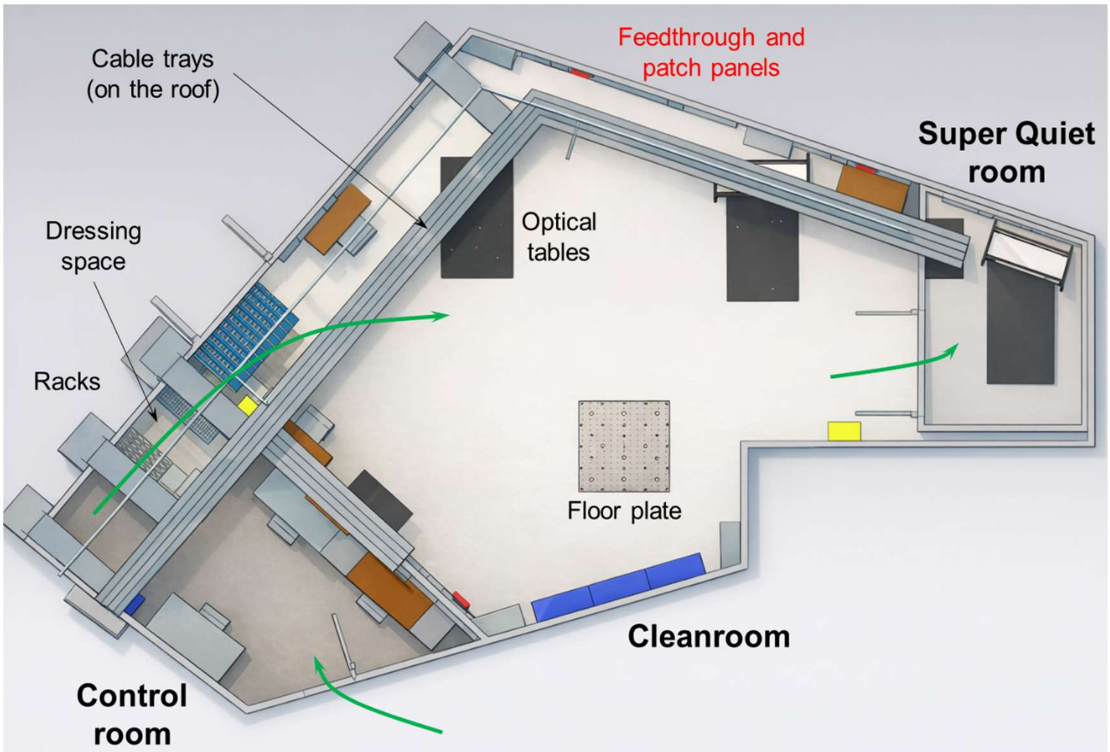

Figure 1. Nanomotion laboratory layout showing the cleanroom, super quiet room, and control room; and some of the infraestructure used.

for improved feedback loops, more stable systems, or dynamically responsive components. On the other side, the laboratory focuses on research tasks. For this, it explores new commercially available products that might be relevant (controllers, actuators, displacement sensors), develops new algorithms for improved feedback or metrology, and evaluates other relevant equipment.

Across these activities, our laboratory targets sub-nanometre measurement resolution (interferometry and capacitive sensors), <50 nm runout after correction (video-based LUT), low trigger jitter at 1 kHz (FPGA), and closed-loop bandwidths up to the low-kHz range for optical elements. These targets guide hardware selection, error budgeting, and control design.

The following sections describe some of the projects in hich the laboratory is currently involved at ALBA.

3.1. Interferometer feedback

After years of using interferometers mainly for metrology applications, ALBA is now introducing interferometer-based feedback on beamline components.

The first test was carried out at BL06-XAIRA, using three sensor heads pointing through viewports at the horizontal focusing mirror upstream of the sample position. While the setup is still temporary, it has demonstrated the ability to provide precise simultaneous measurements of the mirror's displacement, pitch, and curvature. The operation of the interferometer in the kHz range of frequency will allow its incorporation to the feedback loop for mirror stabilization in the future.

In the case of BL15-3SBAR—the first beamline designed with ALBA II specifications in mind—interferometers have been incorporated into the feedback loops of the focusing mirrors and monochromator. This beamline is under construction at the time of writing, and interferometers will be added as components arrive, starting with the monochromator expected in the first half of 2026.

3.2. Fast periodic shutter feedback and trigger

Recently opened to users, BL31-FAXTOR is dedicated to fast X-ray tomography and radiography. For time-resolved tomography experiments, a fast periodic shutter will chop the X-ray beam at high frequency (up to 1000 Hz). The controlled speed of the shutter is expected to fluctuate slightly, so we are actively developing a detection and trigger system to synchronize the experiment.

Figure 2. Environment sensor monitoring and history panel. Two weeks of data are shown. Top: temperature sensors; middle: particle counts and relative humidity; bottom: lab door stauts and control room temperature.

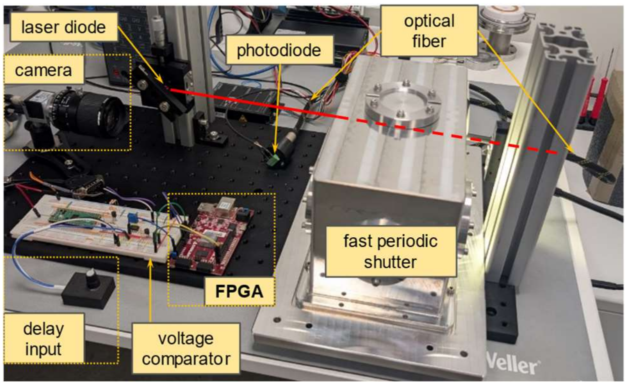

Figure 3. Prototype FPGA-based trigger system for fast periodic shutter synchronization. The setup includes a photodiode signal amplified via a voltage comparator and processed by the FPGA to generate phase-locked triggers for image acquisition.

Symmetrical to the beam path through the shutter, a laser and photodiode can be mounted. The signal captured by the photodiode can be analyzed: its frequency provides an external measurement of the beam chopping and, consequently, the shutter's rotation speed.

Moreover, the group is actively working on FPGA programming to further process the photodiode signal. An FPGA offers the speed and stability needed to generate a phase-locked trigger for the detector to capture an image when the shutter is fully open. This approach ensures deterministic timing and minimizes jitter, critical for high-frequency tomography.

The prototype is shown in Figure 3, and initial tests with a 3D-printed shutter and a camera instead of a detector have yielded very positive results. The photodidode signal is sent to a voltage comparator to condition it for the FPGA input , improving signal integrity and noise immunity. A second input to the FPGA allows the user to delay the trigger to adjust the image acquisition. With these inputs, the FPGA generates the trigger for the camera to acquire the images. In terms of the beamline, this trigger can also be used by other equipment, such as synchronized sample position capture, which is essential for improved tomography reconstruction.

3.3. Runout metrology and online feedback

A key application in synchrotron instrumentation involves rotating samples to acquire data at different angles for reconstruction or increased signal. However, small unwanted motions—such as radial runout, axial displacement, or wobble—can severely compromise the rotation's purpose.

The group has addressed this issue for the sample stage at BL06-XAIRA. A new method for runout measurement was developed, based solely on video acquisition normal to the rotation axis. The video is analyzed frame by frame to calculate rotation and runout. Using this information, a calibrated lookup table for correction can be created. Further details can be found in [2]. Figure 4 shows the measured runout of the stage using this new method: the first measurement was used to calculate the correction lookup table, and the second verifies the result after applying the correction.

The next milestone is to develop an online feedback system for runout correction, based on a multiprobe error separation method. Error separation follows a three-probe, non-symetric arrangement to decouple spindle error harmonics and target shape, as demonstrated in [3] and multiple other works. Correction will be deployed as an open-loop lookup table with planned upgrade to closed-loop overlay. A prototype is currently under assembly. Additionally, the video-based measurement will be employed to corroborate the results obtained.

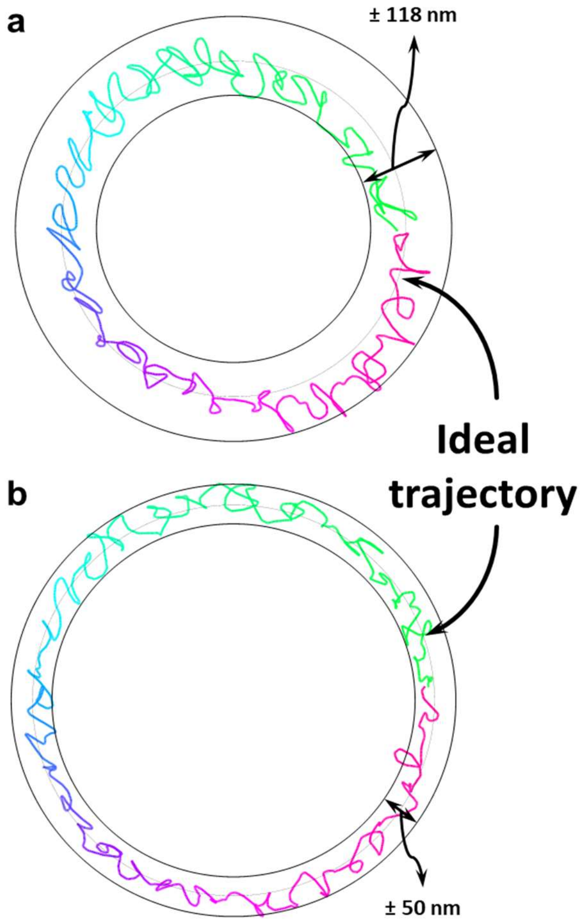

Figure 4. Runout measurement results for the BL06-XAIRA sample stage using video-based analysis. The first dataset (a) was used to compute the correction lookup table; the second (b) verifies the improvement after applying the correction.

3.4. Ptychography scanners

Alongside the ALBA II upgrade, a coherence program is being launched at ALBA. Initial proof-of-concept experiments will be developed in the coming years to gain knowledge about requirements and working procedures. The first of these tests is underway and scheduled to produce results by the end of 2026. The main goal for now is to learn how to run the experiment and process the data.

For the Nanomotion group, these tests are an excellent opportunity to gain experience in mechanics and control. The group will focus on the rapid development of a set of stages with motion controlled via relative displacement measurements from an interferometer between the optics and the sample. The design will follow what is described in [4]. Initial scans will use snake trajectories with overlapping and stability yet to be defined. Once the initial set is ready, improvements to the mechanical assembly will follow using the dynamic error budgeting method, and control will be designed using a mechatronics approach. These concepts are expected to significantly enhance the performance of complex mechatronic systems, as demonstrated by other synchrotron facilities.

3.5. FPGAs

The last major objective of the group is to develop proof-of-concept applications using Field Programmable Gate Array (FPGA) chips. While programming these systems is more complex than regular scripting, the potential gains in speed and deterministic operations justify the effort.

Currently, small applications for device synchronization via triggering are being developed, such as the fast periodic shutter at BL31-FAXTOR mentioned earlier. There is also a list of potential systems that could benefit from FPGA-based control, either by replacing existing components or by modifying their control architecture, which would be tackled in 2026 and 2027.

4. Conclusions

The Nanomotion Laboratory at ALBA has been established to address the demanding requirements of next-generation synchrotron instrumentation, driven by the ALBA II upgrade. Its infrastructure—featuring an isolated slab, cleanroom environments, and a passive ultra-stable space—provides a controlled setting for precision metrology and motion control development.

Current projects span interferometer-based feedback for optical components, FPGA-driven synchronization for high-speed experiments, advanced runout metrology and correction, and the design of ptychography scanning systems. These efforts aim to integrate high-resolution sensing, deterministic control, and dynamic error budgeting into the workflow of the beamlines of ALBA and ALBA II.

Beyond supporting ALBA's internal developments, the laboratory seeks to engage with the broader precision engineering community. Opportunities for collaboration include nanometrology, mechatronic design, FPGA-based control, vibration-decoupling optomechanics, and advanced scanning strategies. By sharing expertise and fostering joint developments, we aim to accelerate innovation in precision engineering for large-scale scientific facilities.

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