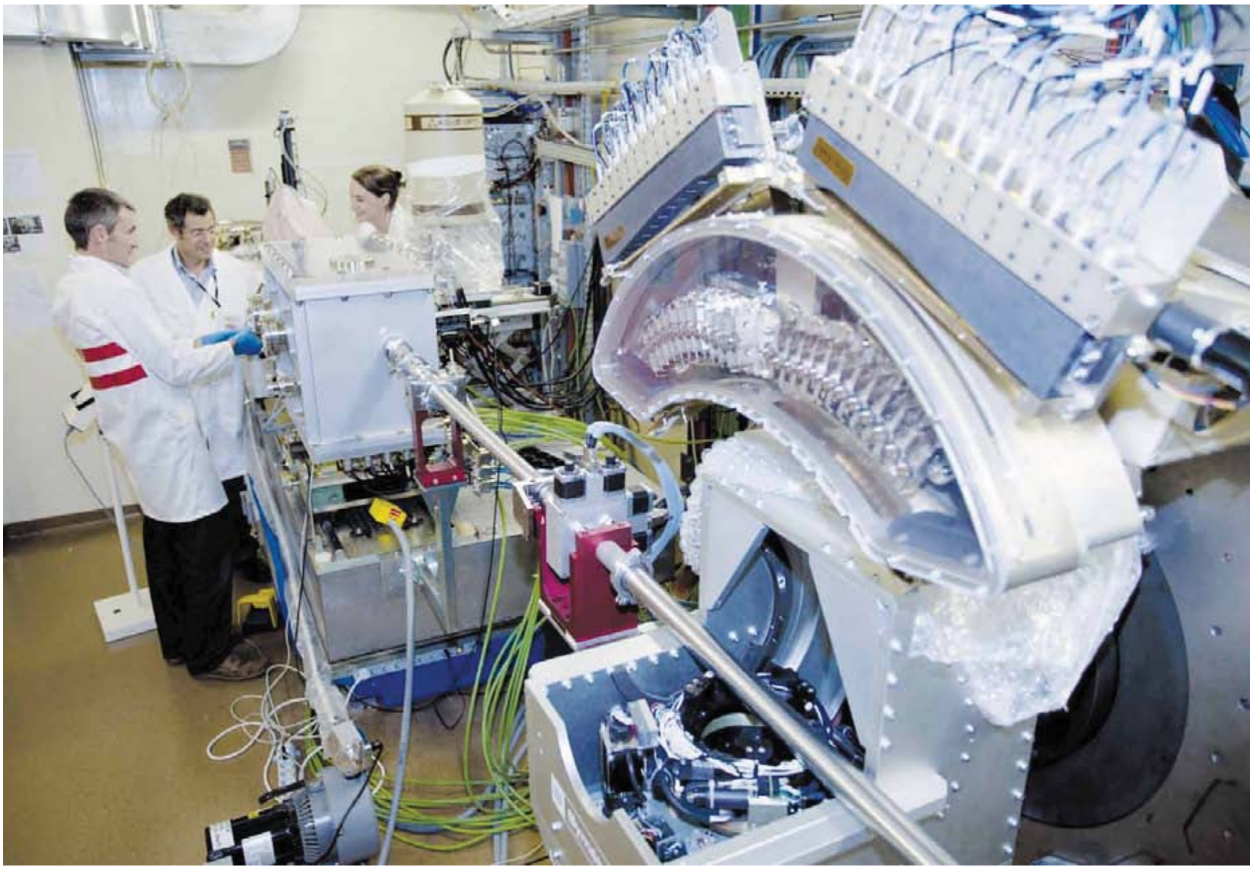
RESEARCH AND DEVELOPMENT

# Customized optimization of SOLEIL beamlines

SOLEIL has 29 beamlines planned for 2015, of which 26 are already operating today. To be able to conduct the research needed by those who designed and run these beamlines, as well as the scientific communities who ask to use them, all groups at SOLEIL are mobilized. They are adapting or developing equipment to maintain at the highest international level the scientific results obtained at SOLEIL. The work is "customized" to overcome problems specific to each beamline.



In the experimental hutch of the MARS beamline, with its diffractometer on the foreground.

## First came the building

The machine part - accelerators and storage ring - and SOLEIL beamlines were built on a concrete slab 80 cm thick, placed on 600 concrete piles driven down to a depth of 15 meters. These are therefore balanced "on stilts" on a separate structure from the rest of the building to minimize the impact on the electron beam trajectory of vibrations produced around the site (vehicles on neighboring roads, for example), and prevent settling due to the presence of expanding clay in the soil.

These already restrictive provisions, which meet stringent stability specifications, are far from sufficient for Nanoscopium. This 155-meter-long beamline (see Rayon de SOLEIL 21, p9) requires constraints that are 30 times greater, especially with regard to rotational deformities of the structure.

Imagine wanting to pierce an apple with an arrow placed in front of the Eiffel Tower, aiming from... Athens. This is equivalent to what is expected, in terms of accuracy, from the X-ray beam the wall of the storage ring and hitting a sample placed in the Nanoscopium experimental hutch. Effects related to wind or temperature – likely to cause deformities much greater than the stability criteria imposed - are parameters normally taken into account in architecture. But when you have to consider vibrations on such a precise scale, this becomes much more unusual.

The originality of the project lies more in the approach than in the means used. Since 2008, plans show, to the nearest millimeter, at what points beamline stability must be maximized. Then, performance is achieved by the geometry and

Installation of a mirror in the optics hutch of the DEIMOS beamline.

thickness of different independent concrete slabs, tailored to each of these "strategic" points, upon which the beamline will rest. Faced with such a challenge, we had to take risks and get started, because there were no precedents to rely on. Mission accomplished: tests at the end of October showed that the Nanoscopium hutches are stable to the said specifications.

## A la carte insertion devices

At SOLEIL, 21 beamlines operate with insertion devices, sometimes with two different undulators. However, no two are completely identical, and some of them have been entirely designed at SOLEIL to meet the exact requirements of researchers (see insert). But this willingness to customize does not prevent having an overview: among the components of undulators, some are present in several different types, like building blocks. A «duplication» strategy is illustrated by the fact that the modulator wiggler used to create the ultra-short electron bunches for the slicing experiments carried out on the CRYSTAL and TEMPO beamlines, is also used as the light source for the PUMA beamline (see Rayon de SOLEIL No. 20, p11): a two-in-one wiggler, if you like.
More conventionally, but always with machine optimization in mind, canted undulators have permitted two beamlines to be installed on a single straight section of the ring, for the two parts of the PROXIMA2 beamline and the Nanoscopium / ANATOMIX beamlines. And, in general, the whole optical setting of the ring has been designed to satisfy the users of the beamlines in terms of the size of the electron beam source points, by guaranteeing excellent machine performance (notably the life of the beam).
Another very popular feature: after maintenance periods, just a weekend of beam is sufficient to reach the vacuum necessary for conducting experiments, so users are not penalized. This advantage is due to having chosen to cover the walls of the vacuum chambers with NEG1 deposits over 60% of the ring. This makes the conditioning of the ring much shorter when starting-up the machine, saving about half the time.

## Cutting edge optics

With beamlines aiming to perform at the limits of current technology, innovation is required. On Nanoscopium, having reliable optics means that, on the active zone, which is one hundred millimeters in length and one mm in width, the acceptable pitch deviation on the mirror surface is below 1 nm. Polishing a mirror to such precision "in one go" is not feasible and local adjustments must therefore be carried out during a second phase, in order to meet the stringent surface specifications required. To these alterations must be linked a nanometrology step in order to verify that the required specifications have indeed been met. However, measuring instruments on this scale do not exist!
This is why, since 2010, the Optics Group at SOLEIL has developed in collaboration with two local companies, EOTECH and MB Optics, an interference microscope that will control these ultra-high precision mirrors but also other optical elements at SOLEIL. Because of its resolution, this instrument has a reduced field of view. To measure an optical surface this is moved step by step under the instrument. A large number of data sets are thus collected. They must be connected after subtracting the internal reference of the interferometer to obtain the topography of the optical surface, known as stitching interferometry. One difficulty is that the reference is not absolutely known. The solution under development is based on the fact that the same point on the surface is measured several times, each measurement involving a different point of the reference. Thanks to the resolution and stability of the instrument and to the redundancy of the measurements, the test surface and the reference are both reconstructed.
The microscope and stitching algorithms, in which synchrotrons and optics manufacturers have expressed an interest, are currently

- **Nanoscopium :** the first cryogenic in-vacuum undulator (77K) with PrFeB-based magnets.
- **DEIMOS :** in-vacuum undulator resulting from the original combination of two existing concepts - coupling permanent magnets and electromagnets/copper-plated coils - to switch the polarization direction (right/left helicoidal) of the X-ray beam with a frequency of 5 Hz.
- **SIRIUS :** ultra-short period Apple II undulator giving high energy X-rays with linear polarization.

Discussion within the "Conception-Engineering" group.

undergoing validation on test surfaces. As the software has been developed to run in a modular fashion it will be possible, for example to substitute parts with existing SOLEIL software; yet again, as for sources, there is a desire to make the most of our existing material.
SOLEIL beamlines will benefit from another development of the Optics Group, alternate multilayer gratings (AML). Under specific beam incidence conditions, the alternate multilayers have both the advantages of a multilayer grating and a crystal as they allow it to choose the order of diffraction of the incident beam (its energy must be above 1000 eV for this), and they have "multilayer behavior" by greatly increasing its reflectivity.
The preparation of these rather complex gratings is the result of a collaboration between the Horiba Jobin-Yvon company, SOLEIL and the Optics Institute. Jobin-Yvon provides the "network substrate" (based on Si) etched according to the target period and depth requested. Then, at SOLEIL, the etching is characterized by AFM. As these parameters are known, diffraction efficiency is optimized by computer simulation, to define the optimal multilayer. Then multilayer deposits ($Mo_2CB_4C$, $MoB_4C$ or $CrB_4C$) are created at the Optics Institute, with calculated thicknesses. A final check is made on the metrology beamline at the wavelength used. The DEIMOS AML will soon be mounted on the beamline, and then SIRIUS and HERMES will follow.

## Positioning the sample

Positioning of the sample in the photon beam also has to meet very high demands. Whether it is varying the angle of incidence of X-rays for nanoARPES measurements on ANTARES (see Rayon de SOLEIL 21, p4), moving the sample in the X-ray beam on HERMES to reconstruct 2D chemical images using STXM microscopy, or rotating this sample to obtain 3D images on the tomography beamline ANATOMIX, in all cases the resolutions are of the order of several tens of nm. On these scales the mechanics are never perfect. The periodic defects of guiding using ball-bearings or rollers are avoided by replacing these movements with flexural deformation systems, which allow precise displacements on a nanometer scale. Areas to analyze can reach up to several millimeters, so the positioning devices use a «two-stage» mechanism; the first, fully designed by the SOLEIL Design and Engineering Group can move over the sample where each zone is then finely scanned by the second commercially available stage (total stroke of 50 microns for ANTARES). Thus, a mosaic of areas is analyzed consecutively.

As for the buildings, discussed above, sensitivity to vibration and heat need to be taken into account. To minimize the effect of temperature variation, the materials chosen have low coefficients of thermal expansion, piezoelectric motors are used and therefore do not warm up at all when stopped, and assembling tricks, using the direction in which expansion takes place, neutralize the effects. These effects are even more critical in the case of instruments under vacuum (HERMES), because of lower heat dissipation.

The temporal dimension also needs to be taken into account: on Nanoscopium, the relative positions of the optical elements (mirrors, slits) producing a secondary X-ray source must be micron stable for 8 hours to obtain a stable nano-beam on the sample that is 70 meters away. To measure this, a kind of electronic "water level" is installed stretching from the beam monitors in the ring to the granite stand where the sample will be placed, more than 150 meters away. This Hydrostatic Leveling System (HLS) has been optimized by SOLEIL's Alignment and Metrology Group, based on a commercially available instrument.
Then, during analysis of the sample, all nano-movements must be monitored and controlled. Again, there are two measurement levels: for a resolution of a few tens of nanometers, commercial optical encoders suffice. For greater precision, specific interferometers are being developed at SOLEIL. That of ANTARES is in operation, while that of HERMES is being defined. Information (analysis of interference fringes created between a reference light beam and a measurement beam) is used to correct mechanical defects that distort movement.

## Detecting the signal

Third generation sources such as SOLEIL allow for experiments requiring space- and time-resolved measurements, while maintaining wide information dynamics. To have detectors that match the performance of its machine, SOLEIL collaborated with the Marseilles Center for Particle Physics (CPPM) and the ESRF beamline, CRG-D2AM, to develop a new generation of so- called hybrid pixel 2D detectors (see Rayon de SOLEIL No. 21,

p20). Adapted to the characteristics of the hard X-ray beamlines, these consist of a sensor the rear face of which is pixellated, each pixel being coupled to an electronic counter etched on a dedicated circuit. Similarly to CCD cameras, these "XPAD3" detectors measure the number of photons emitted by the sample and their positions, but they also offer several extra advantages. An energy threshold can be set beyond which these photons are detected, which reduces noise and accurately identifies the emitted photons, especially during experiments using a polychromatic incident beam (Laue diffraction). Another advantage: the sensor can be in standard Si or CdTe, more sensitive to high-energy X-rays (>15 keV).
Methodological developments have also been made in terms of the XPAD3 operating system in order to significantly improve its measuring abilities: it is possible to accumulate recordings of photons detected over hundreds or even thousands of repeat cycles of the same experiment with a duration of the order of one second. By synchronizing the XPAD and the experimental cycle, data are stored in memory registers corresponding to N phases of the cycle, and ultimately the XPAD provides, not Nx1000 images, but N, which greatly simplifies data treatment.
Finally, in a synchrotron such as SOLEIL, photon pulse durations are used to study dynamic phenomena on the scale of picoseconds ($10^{-12}$ s), and thanks to the new slicing technique (see Rayon de SOLEIL No. 20, p11) even femtosecond pulses ($10^{-15}$ s) have been reached. For this, a sample is excited with a laser and then probed with synchrotron radiation at different time intervals after excitation. These "pump-probe" measurements are repeated at the laser frequency – i.e. up to 10 kHz - to obtain sufficient amounts of data. For this type of experiment, the electron bunches circulate in the ring at a frequency of 847 kHz. There are, therefore, almost 85 times more "probe" "than pump", so it is necessary to select the photon pulses immediately following laser excitation. Until now, the solution had been to use a mechanical chopper to stop the "surplus" electron bunches, an expensive solution difficult to set up and regulate, and limited to a frequency of 1 kHz. Using XPAD 3.2, the selection is now made at the detection level: only the photons emitted after the pulse probe of interest are counted. For this, an electronic signal synchronized with the radio-frequency system of the storage ring successively inhibits and disinhibits all the pixels of the counter, during the passage of electron bunches. An electronic "chopper" that has already proved itself on the CRISTAL beamline.

## ... and acquisitions "on the fly"

Faced with changes in the means of taking measurements, and how to optimize beam time, the challenge is to obtain the maximum of data in the shortest time - while having the possibility, before launching an experiment, of validating the experimental conditions to ensure the collection of relevant data is possible. Hence, the need to have real-time feedback on the current acquisition. This is the goal of fly-scan, the principle of which is to measure several experimental dimensions in parallel, e.g. the position of the detector, the intensity of the photon beam and experimental information (fluorescence, absorption, or diffraction measurements with the XPAD, for example), and not step by step, but on the fly. One dimension is thus measured continuously and all the others are associated with it, the idea being to add as many extra dimensions as desired.
This unprecedented "made in SOLEIL" system of simultaneous multi-technique data acquisition is based in part on the existence of a clock common to all measurement systems (distributing an electronic signal, the role of which is to synchronize acquisitions). It also requires an ad hoc software infrastructure developed around the NeXus format (see Rayon de SOLEIL 20, p20), which allows for data homogenization. When the synchronizing signal triggers one of the actors of the system, it generates a data series stored in an individual elementary file specific to the device activated. And, all individual files relating to the experiment are merged into a single file as output. It thus becomes possible to correlate completely independent systems, all information having been brought to the same time base.
SOLEIL fly-scan was initially developed for Nanoscopium and will eventually be offered to other beamlines.
Setting up this acquisition system also involves a whole management structure - storage, processing and availability to users – the generation of a huge data stream involving, notably, SOLEIL's data storage infrastructure.
A huge challenge that SOLEIL's Computer and Electronics Division is now trying to meet.

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1- NEG (non evaporative getter): titanium zyrconium and vanadium alloy deposited in a layer ~ 1 micron thick.

**In the "Detectors" laboratory.**