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The ALBA Synchrotron Light Source

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Summary. ALBA is the Spanish third-generation synchrotron light source. It is located in Cerdanyola del Vallès (Barcelona) and constitutes the largest scientific infrastructure in Spain. The facility consists of an accelerator complex providing 3 GeV electron beam and several experimental beamlines, with photon energies currently ranging from IR up to hard X-rays of tens of KeV. Different synchrotron radiation techniques are available including diffraction, spectroscopies and imaging. [Contrib Sci 12(1):13-21 (2016)]

Synchrotron light

Synchrotron light is electromagnetic radiation that is produced when, within an accelerator, the circulating bunches of charged particles (typically electrons) are accelerated by the magnetic fields that are used to curve their trajectory in order to keep them inside a circular orbit. What we call "synchrotron light" is not something new. It has always existed in our universe. In a star, electrons travelling at almost the speed of light emit synchrotron radiation when they are under electromagnetic forces. However, in the last 75 years, humankind has been able to produce synchrotron light by building synchrotron facilities.

In the last 50 years, synchrotron light facilities have become a major research tool to observe the properties of matter thanks to their powerful properties. As the brilliance of synchrotron light is so much greater than that of more conventional sources, such as rotating anode X-ray tubes, the precision of the measurement is also many orders of magnitude better, being the essential reason why synchrotron light sources are today absolutely necessary for competitive fundamental or applied research. And why is synchrotron light so bright? In a synchrotron facility, as the particles are travelling at speeds close to that of light, the light they produce is confined within a cone in the direction of propagation of the particles that can be contained within fractions of a milliradian. Also, synchrotron light can provide a very broad range of wavelengths: from infrared to hard X-rays, containing also soft X-rays and UV. In addition, the size of the light source is related to the size of the electron bunch. In a modern accelerator the latter can have a cross-section of only a few tens of micrometers.

The combination of a small source and a small angle of emission implies an extremely high brilliance (it should be noted that brilliance is a measure of the flux of photons emitted per unit area and unit solid angle within a certain wave-

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length bandpass) and the very broad range of wavelengths available means that this very high brilliance extends over a large range of the electromagnetic spectrum. In practice, the brilliance of synchrotron light is trillions of times greater than that of other conventional sources of light over most of the range of the electromagnetic spectrum. Moreover, not only the brilliance is very high but synchrotron light is also polarized in the plane of the orbit, something exceptionally useful for the study of magnetic properties of materials, and, as consequence of the electrons travelling in short regular bunches, the light is emitted in very short pulses lasting around a few tens of picoseconds (a millionth of a millionth of a second, or 10^{-12} seconds). This latter property makes synchrotron light sources highly suited for the study of short-lived phenomena.

The ALBA accelerators

The ALBA accelerator system consists of a linear accelerator (Linac) (where electrons reach 100 MeV), a low-emittance, full-energy Booster (where electrons are accelerated to 3GeV), and the Storage Ring (where electrons are injected and stored for the synchrotron light emission) (Fig. 1). The Booster (250 m of circumference) and the Storage Ring (269 m) are both hosted in the same tunnel (Fig. 2). The lattice is optimized for high photon flux density, with a nominal current of 250 mA. There is a large number of straight sections (24) available, whose essential role will be explained below, despite the relatively short circumference, thanks to the very compact lattice design, which incorporates a quadrupolar field component in the dipoles. The vacuum chamber has more than 20 windows for the light extraction. Twelve of them are presently used (2 for accelerator diagnostics and 10 for beamlines, both operational and under construction), and the others witness the large potentiality of ALBA for the future.

ALBA is a 3rd generation synchrotron facility. That means that its design incorporates long straight sections in between the cells containing the electron optics. In these straight sections the electrons fly freely (i.e., no synchrotron light is emitted as a baseline). However, these straight sections are used to house ad-hoc multipolar magnetic structures, named insertion devices (ID), which force the electrons to undergo more or less exotic trajectories, the simplest being a sinusoidal one. Depending on the dimensions of the excursions imposed on the electron beams, insertion devices are conceptually sub-divided between wigglers—so named when the excursions imposed on the electrons are large relative to the beam angular divergence—and undulators—when the excursions are comparable to the beam angular divergence.

The light emitted by the ID is even brighter than that generated at the bending magnets. This can amount to an enhancement of several orders of magnitude and, furthermore,

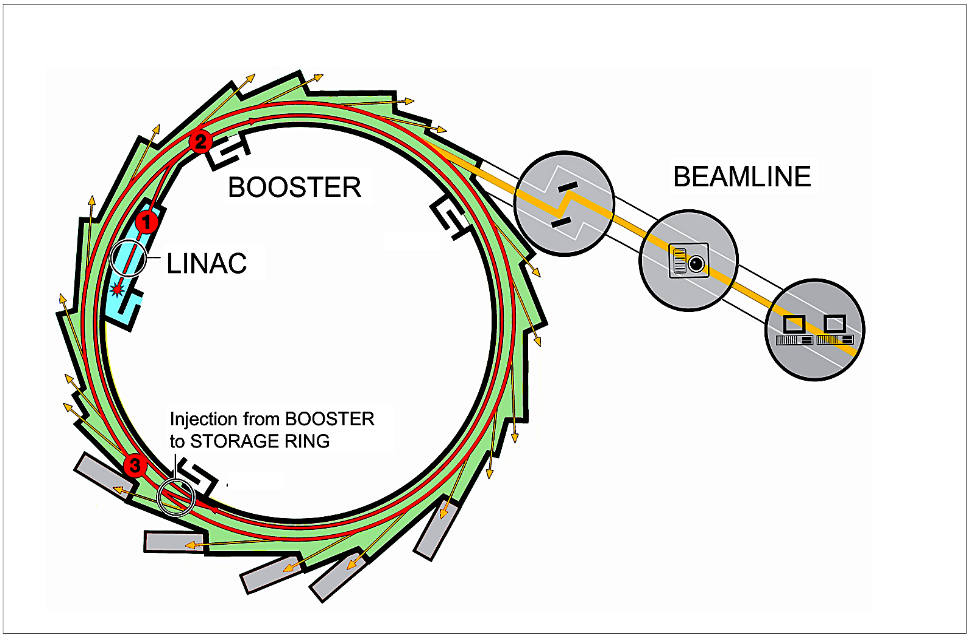

Fig. 1. Scheme of the Accelerators complex and the structure of a beamline.

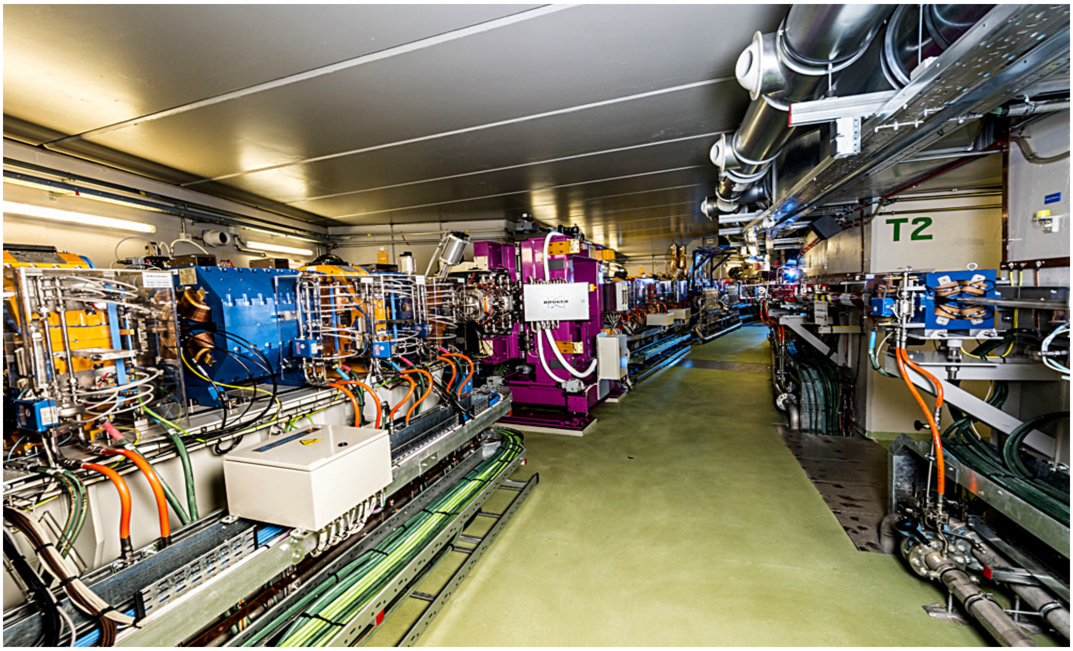

Fig. 2. View of the tunnel of accelerators. Storage Ring (left). Booster (right).

insertion devices can be tailored to the specific requirements of a given experiment and may be substituted easily without changing all the magnetic lattice of the Storage Ring. This significantly increases the useful life of the facility.

The ALBA Accelerators run on a 24 h a day, 7 days a week basis, for periods that usually are 4 to 5 weeks long. In 2015, more than 4300 h were devoted for users with a beam availability of 97.3%. About 1400 h were dedicated to the optimization of the accelerators for the users as well as to testing new developments.

In 2015, the injection in top-up mode has been consolidated. In the top-up mode injection, the current in the Storage Ring is kept constant, injecting almost continuously a very small fraction of current to cope with the beam losses due to the finite lifetime of the beam. In this situation, the front ends (the tube connecting the sources of light to the beamlines), interfaces between the accelerator and the beamlines wherein experiments with synchrotron light are performed, remain open during injection. This injection mode ensures a constant thermal load on the accelerators and on the optical components of the beamlines, which increases greatly the position stability of the photon beam at the sample. This, together with the fact that a constant photon flux at the sample means a constant signal level at the detectors, sensibly improves the data quality of the experiments performed at ALBA.

In May 2015, a fast orbit feedback system (FOFB) came into operation, stabilising the photon beam at the source location at frequencies up to 100 Hz. The immediate conclusion of this development is that now the orbit in the Storage Ring is much more stable, better than 600 nm (rms) in the horizontal plane and 100 nm (rms) in the vertical plane; in other words, the electron beam is stable to less than 1% of its beam size (at the medium straight, typical reference point where light is generated to be fed to the experimental beamlines), placing ALBA at the frontier of the beam stability among the synchrotron facilities worldwide.

An additional development, a bunch-by-bunch transverse feedback system, has also started operating in 2015. This system fights electron beam instabilities on a bunch-by-bunch basis, acting directly on the individual bunches by damping high frequency oscillations (up to 250 MHz) that may affect the brilliance of the photon beam.

The beamlines

Once synchrotron light is emitted by the magnet systems, it is redirected through the front ends to the beamlines, where experiments are performed by the users. ALBA started operation in May 2012 with seven beamlines dedicated to different scientific fields, mainly physics, chemistry, life sciences, materials science, cultural heritage, biology and nanotechnology. Two new beamlines were initiated in 2014, one of them in operation already in 2016 and the second one to become operational in 2018 and one additional beamline has been started in 2016. So, the current portfolio of ALBA is of 10 beamlines: 8 operational, and 2 under construction. As mentioned in the previous section, the ALBA Synchrotron is designed to host more than 20 beamlines (Table 1).

According to their scientific applications, ALBA beamlines can be divided into three groups:

a) Biosciences

MISTRAL. X-ray full-field transmission microscope for cryotomography of biological material of very high spatial resolution, producing 3D images of complete cells without the need of sample slicing.

NCD. It studies samples with large (SAXS) and small (WAXS) periodicities. Very useful to analyze biological applications (fibers, tissues and solutions) as well as polymers.

XALOC. It is devoted to protein structure determination through X-ray crystallography. It is available for working in control remote system, sending the samples to the beamline staff and controlling the experiment from outside the facility.

MIRAS. Infrared microspectroscopy for the study of molecules. This beamline was operational for users in the last months of 2016.

XAIRA. A new microfocus beamline for macromolecular crystallography. This beamline will offer further insight of how biological systems function at the atomic level, determining the three-dimensional structures of macromolecules and complexes. The microfocus beamline will deliver a small X-ray beam of the order of 1 micron (1µm) at the sample position. The small beam size will allow tackling an increasing number of important projects that are limited by the size of the crystals or by the radiation damage effects. These projects include membrane proteins, protein complexes, DNA-protein complexes and radiation-sensitive proteins. The beamline is planned to be ready for first experiments in 2020.

b) Condensed matter

Especially magnetic and electronic properties and nanoscience.

CIRCE. Photoemission microscopy for chemical imaging of the surface and photoemission spectroscopy with samples at pressures up to 20 mbar (particularly challenging, since usually photoemission experiments need to be performed under strict ultra-high vacuum conditions) for investigating surface chemical reactions and surfaces of liquid samples.

BOREAS. X-ray magnetic circular dichroism (XMCD) and X-ray magnetic linear dichroism (XMLD) techniques for the study of advanced magnetic materials. With a second experimental end-station devoted to soft-X-ray magnetic scattering.

LOREA. Low-energy ultrahigh resolution angular photoemission beamline for the understanding of the electronic structure of graphene-based material, topological insulators and other advanced materials. This beamline is currently in construction and will be operational in 2018.

c) Materials science

With applications in chemistry, environment and cultural heritage, among others.

MSPD. Powder diffraction beamline with two end-stations: diffraction under high pressure for analyzing the crystalline structure of matter under extreme pressure (up to –50 GPa) and high resolution and high speed diffraction for the study of chemical kinetics, phase transitions, etc.

CLÆSS. Absorption and emission spectroscopy for XANES/EXAFS during chemical reactions under conditions close to those relevant to industrial catalysis.

MIRAS. This beamline, already mentioned above, also has applications in this field thanks to its capability for studying compound plastics, blends, fillers, paints, rubbers, coatings, resins, and adhesives, polymer interfaces, etc.

Table 1 shows the list of operating and under construction beamlines, including the number of end-stations, the experimental techniques and their scientific applications.

The users

The ALBA Synchrotron is a public consortium, funded in equal parts by the Spanish and Catalan governments, and is intended to be a useful tool mainly for public research. Most of the experiments performed are from public institutions although private access is also available. The ALBA Synchrotron opens two calls per year for granting access to the beamlines for public research projects. The received proposals are initially checked for their technical feasibility and are evaluated by external international panels. The main criterion for the evaluation is scientific excellence. The output of the call is based on a ranking that distributes the available beam time. Since

Table 1. Beamlines, techniques and applications

Port	Beamline	End-stations	Experimental techniques	Scientific applications
4	MSPD	2	High resolution powder diffraction. High pressure diffraction	Structure of materials. Time resolved diffraction
9	MISTRAL	1	Soft X-ray full field transmission X-ray microscope. Optimized on the "water window"	Cryogenic tomography of biological objects. Spatially resolved spectroscopy
11	NCD	1	High resolution small and high angle X-ray scattering/diffraction	Structure and phase transformations of biological fibres, polymers, solutions. Time resolved X-ray studies
13	XALOC	1	X-ray diffraction from crystals of biological macromolecules	Macromolecular crystallography, with particular emphasis on large unit cell crystals
22	CLÆSS	1	EXAFS, XANES, Quick-EXAFS	Material science, chemistry, time resolved studies
24	CIRCE	2	Photo-emission microscopy (PEEM). Near atmospheric pressure photo-emission (NAPP)	Nano-science and magnetic domain imaging (PEEM). Surface chemistry (NAPP)
29	BOREAS	2	Circular Magnetic Dichroism. Resonant Magnetic Diffraction	Magnetism, surface magnetism and magnetic structures
01	MIRAS	1	Infrared microspectroscopy	Life sciences, food sciences, materials science
20	LOREA	1	Angle-resolved photo-emission spectroscopy	Polarized electron spectroscopies, band structure determination
	XAIRA	1	X-ray diffraction	Microfocus Macromolecular crystallography

2012, when the operation with external users started at ALBA, the number of proposals has been continuously increasing in parallel with the maturing process of the facility. The average oversubscription, counting all of the beamlines, was 2.3 in 2014 and 2015. However, the distribution of the oversubscription is not uniform: in CIRCE oversubscription has been above 4 in the last two years, followed by CLÆSS, in which oversubscription has been between 3 and 4.

In 2015, a total of 335 proposals were submitted (34% more than in 2014) and 4980 shifts (of 8 hours) were requested (58% more than in 2014). Most of the granted proposals correspond to Spanish institutions (65%). European institutions represent 31% and non-European countries 4% (Fig. 3).

Industrial users

The Industrial Liaison Office is in charge of the relationships between ALBA and the industrial community.

The main activity led by the Industrial Liaison Office is the relation of ALBA with the industrial sector and the proprietary access to the beamlines, which during 2015 has increased by more than twice with respect to the 2014 period. Almost all the beamlines carried out industrial measurements during 2015. Sixteen different international and local companies came to perform studies at ALBA during 2015. Those companies belong to very different industrial sectors such as pharmaceutical, chemistry, automotive, catalysis, nanotechnology, etc.

In addition to beam time access, ALBA also offers the external usage of its specialized laboratories such as the magnetic measurements, the radiofrequency laboratories and the optical and metrology laboratory. As an example, the magnetic measurement lab has been testing in 2015 different types of high precision magnets such as dipoles and quadrupoles to be implemented in other accelerator facilities.

ALBA is continuously developing new solutions to guarantee an optimal performance of the facility that may be of interest for the industrial community. In that direction, the Industrial Liaison Office works together with ALBA scientists and engineers to establish the best approach to intellectually protect their own developments and, finally, to transfer them to the private sector for their commercial exploitation. As a couple of examples, during 2015, one new patent was registered for an X-ray mirror nanobender and one utility model for a new X-ray detector. Those developments were licensed to the private companies SENER and Alibava, respectively, for their commercialization.

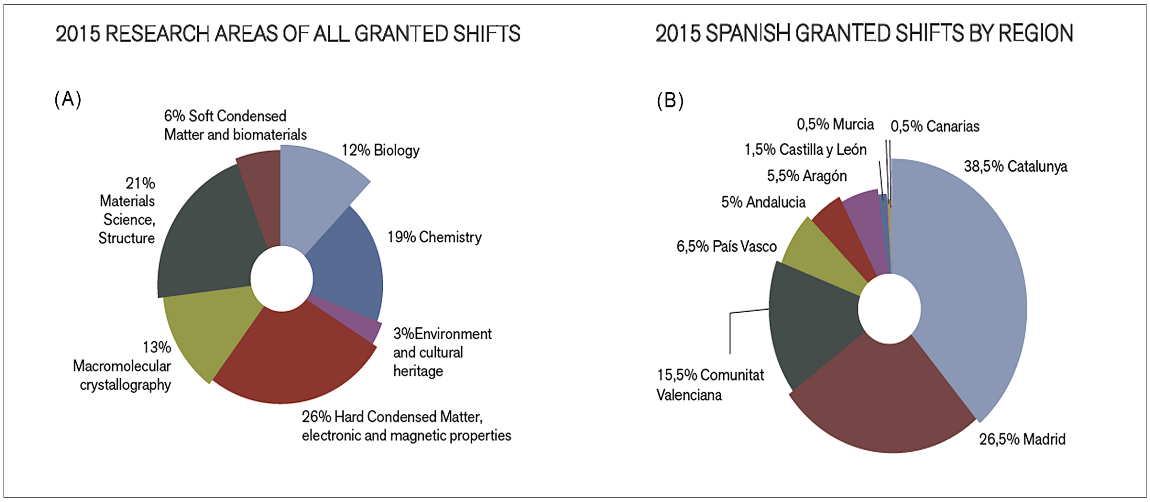

Fig. 3. (A) Research areas of the granted shifts in 2015. **(B)** 2015 Spanish granted shifts distributed by region.

The technological transfer is not only related to patenting and licensing ALBA developments but also to strengthening the relationships with private companies to find common solutions. In 2015, the AGAUR provided ALBA with funding for an industrial PhD. Part of this project is promoted by a private company that wants to increase the knowledge of optical surface cleaning by radiofrequency plasma sources and to implement that technology in its business. It is a three-year project that benefits both the private company and the interests of ALBA, and a significant success story for the public-private synergies and partnerships.

The ALBA project

The idea of building a Spanish synchrotron light source goes back to the early 1990's. The Catalan Government at the time, around June 1992, appointed a Committee with the task of studying the viability and convenience of constructing a synchrotron light facility in the region of Barcelona. By the end of the year this Committee reported to the Catalan Administration with the result that its First Research Plan, approved and presented at the beginning of 1993, included the construction of a synchrotron light source. Also, a Steering Committee constituted by political authorities and chaired by Prof. Ramon Pascual and an Advisory Committee, chaired by Prof. Manuel Cardona and constituted by experts and directors of some European synchrotron light sources, were created. Simultaneously, a program of training fellowships in accelerator technologies was started.

An agreement to finance a detailed study for a Spanish synchrotron light facility was signed in 1995 between the Spanish and the Catalan Governments. To carry out this study a small group of people was assembled under the direction of Prof. Joan Bordas. This group was first incorporated as a new division in the High Energy Physics Institute (IFAE). Later on, the Synchrotron Light Division became a Consortium in its own right between the Catalan Administration and the Autonomous University of Barcelona (UAB). The detailed study commissioned by the Spanish and the Catalan administrations was carried out by the Synchrotron Light Laboratory (Laboratori de Llum de Sincrotró) and published at the beginning of 1998. This was followed by several years of positive evaluations of the project by independent experts and on the 14th of March 2002 a formal protocol between the Spanish and Catalan Governments was signed. The protocol envisaged the funding with equal shares of a synchrotron light source in the municipality of Cerdanyola del Vallès, at some 20 km from the center of the city of Barcelona, and next to the campus of the UAB (Fig. 4).

On the 14th March of 2003, both administrations created the Consortium for the Construction, Equipment and Exploitation of a Synchrotron Light Laboratory, CELLS, and established the structure of its governance consisting of a Governing Council and an Executive Commission.

In June 2003 the first meeting of the Governing Council took place and in October 2003 the activity of CELLS commenced with the start of the build-up of personnel recruitment and, also, with the appointment of two very important Advisory Bodies: the Machine Advisory Committee (MAC; a high level group of international experts in the field of accelerator science and technology) and the Scientific Advisory

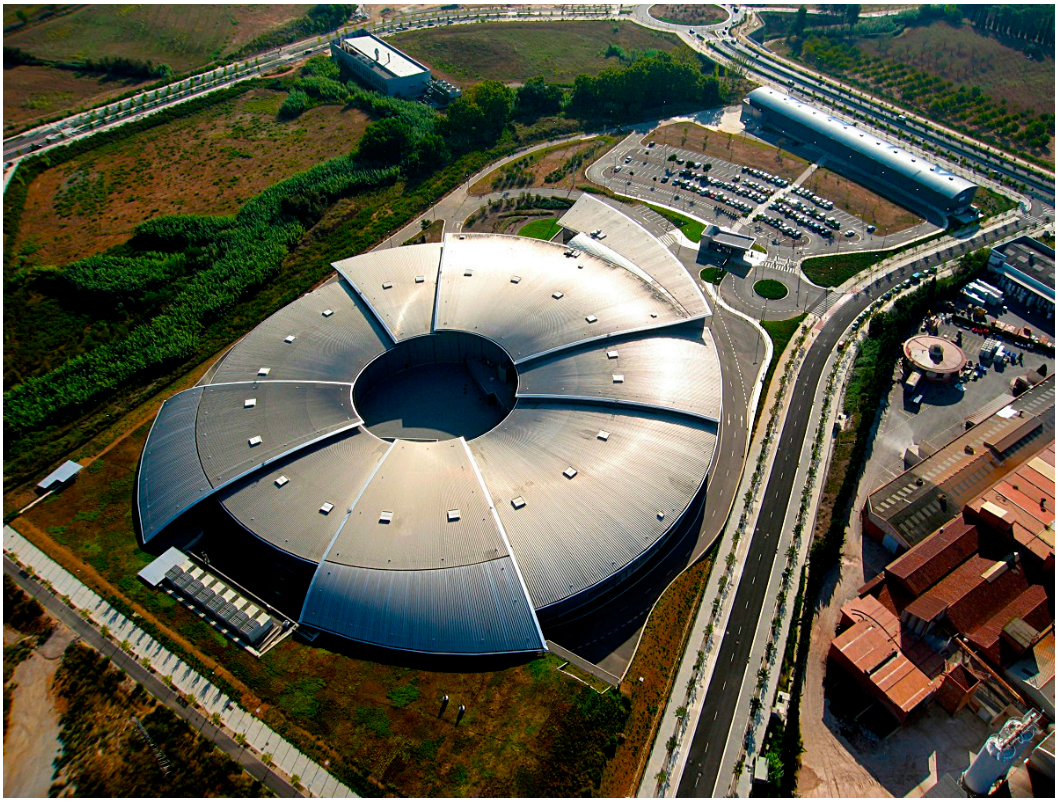

Fig. 4. Aerial view of the ALBA Synchrotron Light Source.

Committee (SAC; a high level group of international experts in the field of synchrotron light science and beamline technologies). MAC and SAC have been meeting about twice a year with CELLS management and staff and, throughout the construction of ALBA, they have advised on the scientific and technical objectives of the facility and have monitored progress in the complex of accelerators and in the beamlines. Still today, SAC meets twice per year to participate in the strategic scientific direction of the ALBA Synchrotron with the aim of ensuring the quality and relevance of the research performed and developed in ALBA.

During the early years of the project the activities of ALBA's staff were carried out in provisional barracks buildings and at a workshop in the neighboring campus of the UAB. This was necessary because the groundbreaking on ALBA site was only initiated in May 2006 after two years of detailed design work of the building and its associated services. In April 2009, the buildings were ready for occupation and ALBA staff migrated to their new quarters. However, during the summer of 2008, the linear accelerator was installed in its bunker and its commissioning completed. From 2010 to 2012, the commissioning of the accelerators and beamlines was done, opening the first one to official users in May 2012.

Today ALBA staff is composed by 200 members organized in the following divisions: Experiments (25%), Computing & Control (25%), Engineering (19%), Accelerators (14%), Administration (8%) plus a Director's Office (9%).

Some examples of experiments carried out at ALBA

More than 1000 researchers per year use the ALBA facility for performing cutting-edge experiments and obtaining results very difficult or impossible to get with their home instruments. Here, we will highlight a few of the most recent and remarkable experiments.

MISTRAL scientists, together with the National Center of Biotechnology of the CSIC (CNB-CSIC) researchers, were able to obtain the first 3D map of the interior of cells affected by the hepatitis C virus, observing the alterations caused by the virus at the endoplasmic reticulum and mitochondria of infected cells. It was also confirmed that these malformations were reversed by treatment with the most common antiviral drugs for

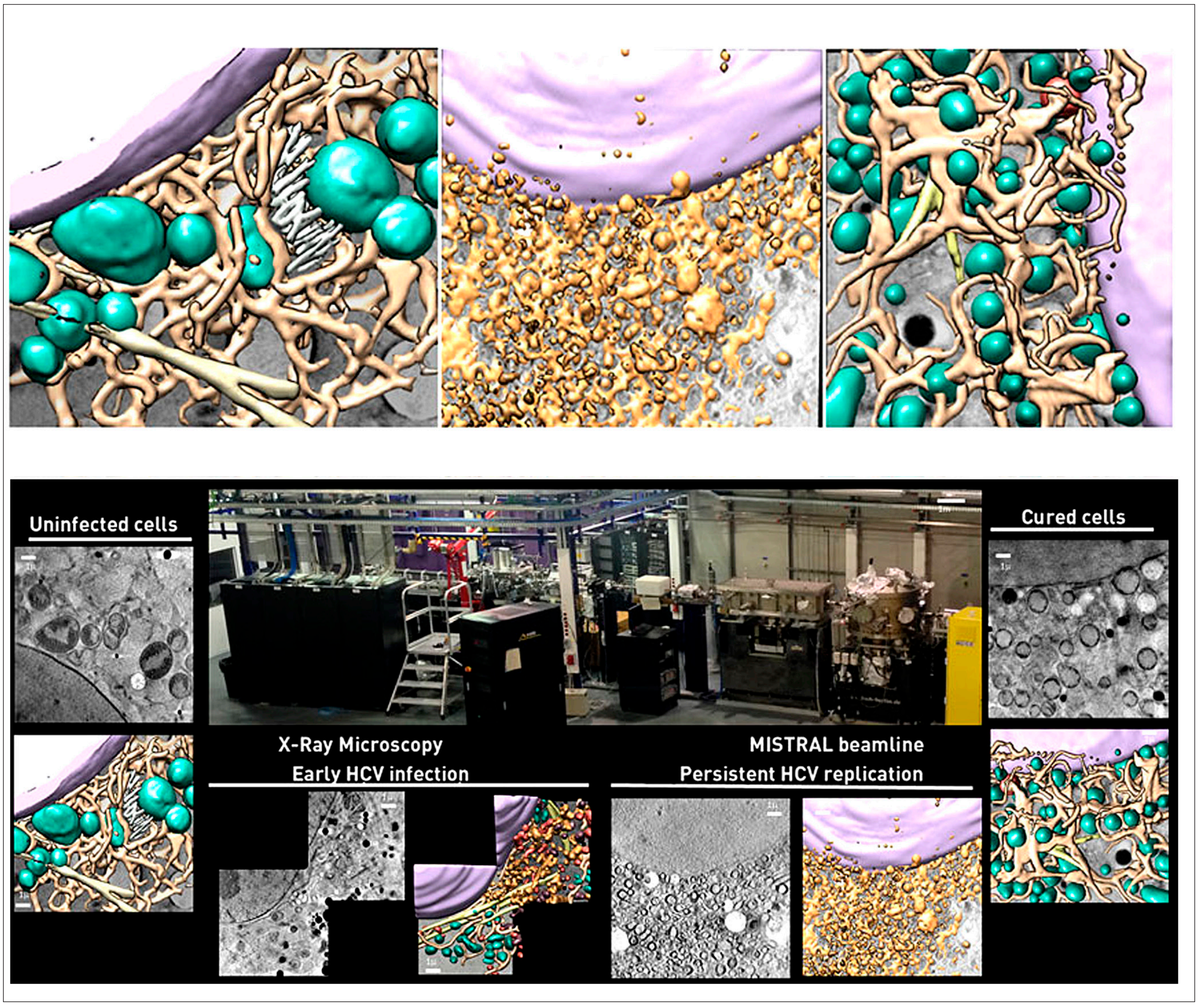

Fig. 5. (A) Interior of healthy cell (left), interior of a cell affected by the hepatitis C virus (center) and interior of a cell after treatment with antiviral drugs (right): cell nucleus (violet); healthy mitochondria (green); healthy endoplasmic reticulum (beige); and altered endoplasmic reticulum (yellow). **(B)** Central image of the beamline and results from the microscope.

hepatitis C. To generate this 3D map, the scientists used the MISTRAL beamline at ALBA, with a new technique called soft X-ray cryo-tomography (cryo-SXT). This method can obtain 3D images of the entire cell in its natural state, that is, without chemical pretreatment, cutting or drying the cell (Fig. 5).

In the PEEM end-station at CIRCE, researchers were able to observe magnetic skyrmions at room temperature in materials compatible with industrial conditions. This breaks an important barrier for their use as nanoscale information carriers in our computers. Magnetic skyrmions are chiral spin structures with a whirling configuration, considered as units (bits) in new magnetic data storage devices. Despite they were predicted in the 80's, they were not evidenced till 2006. However, they could only be seen under very special conditions (at very low temperatures, applying magnetic fields, in bulk samples or films grown by molecular epitaxy). These constraints made impossible their application in industrial devices. Using the X-ray magnetic circular dichroism techniques (XMCD), scientists could solve the skyrmion spin structure. In addition, they were also able to study skyrmion

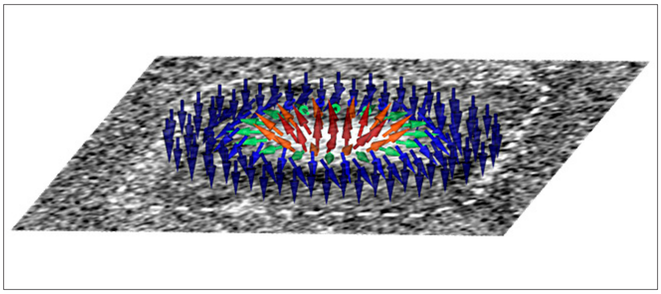

Fig. 6. Sketch of the spin structure of a magnetic skyrmion.

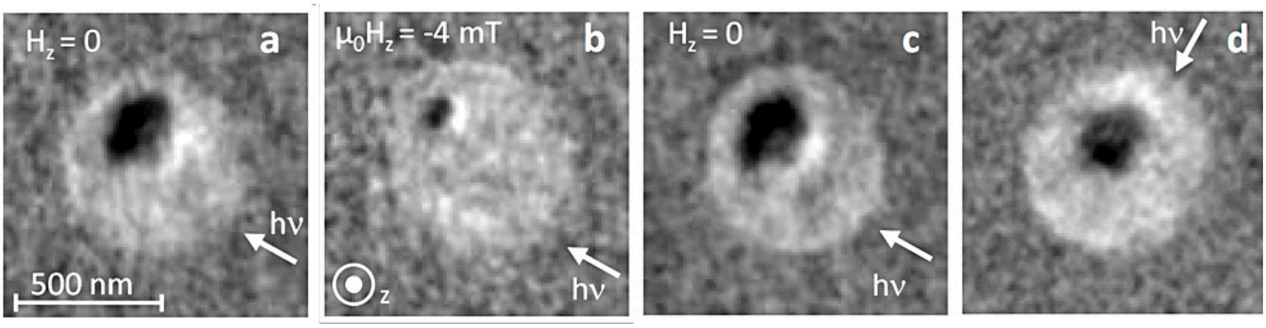

Fig. 7. (A) Magnetic microscopy image of a skyrmion in a Pt/Co/MgO nanostructure. Within the white dot (magnetization pointing down), a circular black/white contrast is visible which corresponds to the in-plane magnetization components. In the skyrmion center, dark grey, the magnetization points up. The grazing X-ray beam incidence is indicated by the arrow. The skyrmion contracts **(B)** under an applied magnetic field of 4mT and relaxes again **(C)** when removing it. **(D)** The chiral skyrmion spin structure is confirmed by rotating the contrast direction (beam incidence) by 90°.

behaviour under small applied magnetic field, demonstrating their stability against perturbations (Fig. 6 and Fig. 7).

At the XALOC beamline, researchers from the Universitat Politècnica de Catalunya - BarcelonaTech (UPC), the Institute of Medical Chemistry (IQM-CSIC) and the University of Glasgow proved the effectiveness of a new drug against malaria. They came to this conclusion after studying the interaction of the 3D crystalline structure of the complex of DNA with the drug.

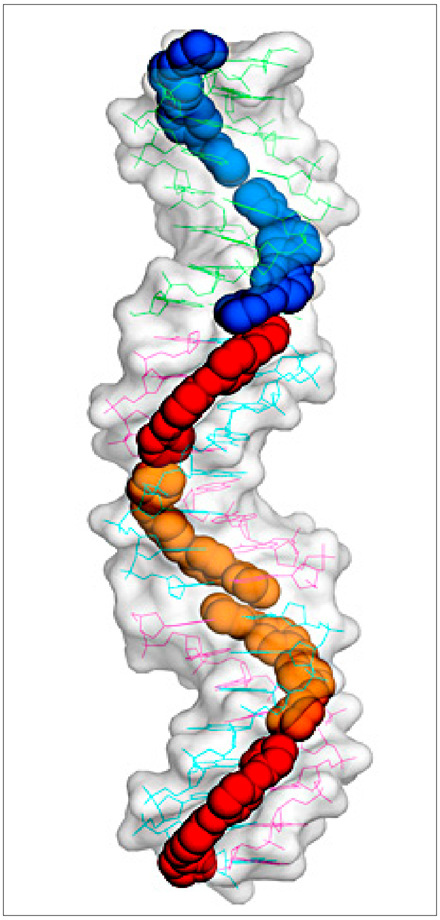

Fig. 8. The drug CD27 completely covers the minor groove of the DNA complex.

The CD27 drug is a complex synthesized by researchers led by Christophe Dardonville at the Institute of Medical Chemistry of the Spanish National Research Council (IQM-CSIC), in Madrid. CD27 is chemically related to diamidines—molecules with two amidines—and has previously been used with success in other *Trypanosoma* species that produce the "sleeping sickness" in Africa and Chagas disease in South America. Results showed how the CD27 drug completely covered the minor groove of the DNA, preventing the typical development of the parasite and causing its death. This research helps to understand this family of compounds and may significantly contribute to the development of new more effective drugs against malaria (Fig. 8).

Conclusions

ALBA is a synchrotron light facility which incorporates the latest technologies available, in operation since 2012. It provides the Spanish scientific and industrial community an invaluable tool for science and innovation and has a huge potential for further developments, which is being gradually exploited with the construction of new beamlines. Located in Cerdanyola del Vallès, just 20 km from the city of Barcelona, it has already become one of the flagship elements of Spanish science and technology landscape.

Competing interests. None declared.