THE SYNCHROTRON LIGHT SOURCE PROJECT IN EL VALLÈS

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An Agreement to form the Consortium for the construction, installation and operation of the El Vallès Synchrotron Light Facility (LLS, Laboratori de Llum de Sincrotró) was signed by the Ministerio de Ciencia y Tecnología (Spanish Ministry for Science and Technology) and the Departament d'Universitats, Recerca i Societat de la Informació de la Generalitat de Catalunya (Catalan Ministry for Universities, Research and the Information Society) on 14 March 2002.

Synchrotron light is radiation emitted by an electron travelling at almost the speed of light when its path is bent by a magnetic field. This can be performed in circular accelerators and particularly low emittance storage rings (synchrotrons) and is an increasingly useful tool in both basic and applied research. The uses of synchrotron light are extremely wide-ranging.

There are currently more than seventy synchrotron light sources in the world including commercially available facilities (used, for example, by computer manufacturers), national research facilities and supranational facilities. Apart from the ESRF in Grenoble, which serves seventeen European countries and Israel, there is no synchrotron light source in Europe, SW of a line from Paris to Trieste. The huge interest in scientific facilities of this type, together with the lack of any such installation in the extensive area of SW Europe, led to the decision by the Government of Catalonia in 1992 to take the initiative to build one. A description is given of the present situation and the main characteristics of the project.

Contents

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* Ramon Pascual is a physicist. He is currently professor of theoretical physics at the Universitat Autònoma de Barcelona and works at the Institut de Física d'Altes Energies (Institute of High Energy Physics). The author would like to point out that this article was made possible due to the contributions of people who have formed part of the team at the Synchrotron Light Laboratory at different times. The author is grateful for both their work and their eagerness and faith in a project that has gone through long periods during which hardly anybody else believed in it. He is especially grateful to Joan Bordas and Josep Campmany for their contributions to this article. It has been relatively easy up until now to say that a synchrotron light source needed to be built here in Barcelona; the complicated stage now, however, is to actually build it.

1. Introduction

The European Physical Society held a meeting in 1994 under the title “Large Facilities in Physics” to analyse the existing large scientific installations in Europe at that time. In addition to the fact that there was no Spanish or Catalan speaker at the meeting, the list of large facilities in Spain[1] was also almost non-existent and limited to an intense magnetic field facility in Zaragoza and a nuclear fusion installation at the Centro de Investigaciones Energéticas Medio Ambientales y Tecnológicas (CIEMAT) in Madrid. Being restricted to the field of physics, other large facilities such as the Canary Islands Astrophysics Institute (where today there is the Grantecan telescope), which was the only large facility in terms of investment (around EUR 100 million), were excluded.

In spite of the fact that the level of science has improved considerably in both Catalonia and Spain over the past twenty years and Spain already participates or is jointly involved in large European consortiums such as the European Space Agency (ESA), the European Laboratory for Particle Physics (CERN), the European Synchrotron Radiation Facility (ESRF), the European Molecular Biology Laboratory (EMBL) and the Institut Laue-Langevin Neutron Source (ILL) in Grenoble, the list of the country's large scientific-technical facilities has improved very little. Aside from the previous exceptions and certain commercial plants, several of which specialise in diagnosis and therapy, there are still no large facilities as in other countries of the European Union even today.

This situation contrasts with the enormous effort put into creating large logistic and cultural infrastructures in recent years. In Catalonia alone, this includes ports and airports, treatment plants, roads and railways and, in the field of cultural infrastructure, the Teatre National, the new Liceu (opera house), the Auditori, the Museu National d'Art, etc. While the majority of citizens consider that these large investments are essential, it is very likely that not so many are aware of the lack of scientific infrastructure in Catalonia.

Of the large scientific facilities that are lacking, a synchrotron light facility is one of the most interesting that can help research in a wide range of applications and make used technologies accessible to enterprises. This is the background for the initiative taken by the Generalitat de Catalunya in 1993 to construct a synchrotron light source with the aim not only of fulfilling the need in Catalonia for a tool of increasing use and with many applications in numerous scientific and technological fields but also of rectifying the lack of large scientific facilities, particularly in the field of accelerators, in Catalonia and Spain.

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[1] The definition of “large facility” is not totally precise. The interpretation made by the MCyT is a broad one and, up until the Ley de Presupuestos Generales del Estado (Spanish General Budget) for 2003, which includes the Synchrotron Light Source, included the following: the Spanish Antarctic Base Juan Carlos I; the Spanish Antarctic Base Gabriel de Castilla; the oceanographic research ship Hespérides; the oceanographic research ship Cornide de Saavedra; the Centro Astronómico de Yebes; the TJ II Thermonuclear Fusion Installation; the INIA High Security Biology Facility; CEDEX; Minisatellites (INTA); the Plataforma de Química Fina (Fine Chemistry Platform); the Plataforma Solar de Almería (Almería Solar Facility); the IRIS Network; the CNM Clean Room; Calar Alto Astronomy Centre; the Teide Observatory; the Roque de los Muchachos Observatory; and the Instituto de Radioastronomía Milimétrica (Institute of Millimetric Radioastronomy) radiotelescope .

Vision and microscopes

It would be difficult to imagine the world without the existence of electromagnetic radiation, which we know as light or the part of the electromagnetic spectrum characterised by wavelengths between 700 nm[1] (red) and 300 nm (violet) that is capable of sensitising the retina of the human eye. This "visible" light enables us to see. In order to be able to see an object, it needs to be illuminated by a light source that is intense enough for a number of photons (a sufficient quantity of light) to be dispersed by the object and the reflected light to be picked up on the retina. The brain processes the signals transmitted from the retina and interprets the characteristics of the object that is seen. Man has improved this vision throughout history by using sources that are sufficiently intense, aided by the telescope to observe distant objects and the microscope for small objects. Observations using the microscope, however, have an inherent limit in terms of the visible light that can be used: The science of optics explains how, with light of a certain wavelength, one will never obtain a power resolution greater than the wavelength itself, which means that no optic microscope can enable structures smaller than 500 nm to be analysed[2].

Present-day science uses the whole spectrum for analysis, and this extends from shorter wavelengths (more energetic gamma rays) to radio waves, and includes X-rays, ultraviolat waves, visible waves, infrared waves, and micro-waves. The use of electromagnetic forms of radiation with wavelengths shorter than visible waves, such as ultraviolet light and especially X-rays, has enabled Man to overcome the limitations of visible light and to be able to appreciate the details of things that would be inaccessible just using visible light. Such uses require strong luminous sources of these forms of radiation (especially to observe small objects) and artificial retinas known as detectors that are required for the computer-reconstruction of the images, given that the reflected light is not picked up by the retina in the eye. The first people to use these techniques in the study of the structures of solids by way of X-ray dispersion were William Henry Bragg (1862-1942) and William Lawrence Bragg (1891-1971).

Aside from the improvements that have been made to luminous sources in research carried out on other analytical instruments, researchers have taken advantage of the undulatory nature of corpuscles, synthesised in the De Broglie ratio l =h/p, where h is Planck's constant and p is the linear moment. Increasing the linear momentum of the particles produces projectiles of a shorter wavelength that enables the smallest details of things to be seen. This can be done, above all, using electrically charged particles that can be accelerated using electromagnetic fields. This is how an electronic microscope works - instead of illuminating the samples with light, i.e. photons, it bombards them with electrons accelerated using a high electrical voltage. By increasing the accelerator power, the momentum of the electrons increases and the associated wavelength is therefore shorter, which increases the resolution of the microscope. The first electronic microscopes were built by Max Knoll (1897-1969) and Ernst Ruska (1906-1988) in 1931; by 1934 they had already exceeded the performance qualities of the best optic microscopes.

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[1] A nanometre (nm) is equal to one thousandth of a micron (10-9m), a length that is equivalent to approximately ten atoms in a row.

[2] To get an idea of what this means, a human hair has a diameter of around 200,000 nm, a cell approximately 10,000 nm; a cold virus around 40 nm; a protein around 10 nm; while DNA chains are around 1 nm thick..

In order to fulfil the majority of the anticipated commercial and academic requirements in the field of synchrotron light in Catalonia, Spain and SW Europe, the First Research Plan (1993-1996) of the Generalitat de Catalunya gave official status to promotion for building a synchrotron light facility in Catalonia for the community of users in the aforementioned geographical area as well as other foreign users. The decision was based on a feasibility report carried out in July 1992 by a commission made up of scientists from the three existing universities at that time in Catalonia, the Spanish Consejo Superior de Investigaciones Científicas, the Departament d'Ensenyament (Ministry of Education) and the Departament d'Indústria (Ministry of Industry), together with experts working in foreign synchrotron light facilities. The commission was appointed and formally set up on 4 September and the feasibility report completed by the end of 1992, which was then approved by the Executive Council of the Generalitat de Catalunya on 9 February 1993.

Groups of experts in related areas and also groups of users of synchrotron light in Spain were also consulted during the second half of 1992. The Generalitat de Catalunya's initiative, which has been endorsed in its subsequent Research Plans, was made more specific through the establishing, by Decree 89/93 of 9 March, of a Steering Committee, which was set up on 31 March[2]. A personnel training plan was also set in motion with a call for applications for ten grants aimed at young graduates and recent PhDs beginning their professional experience in the field of accelerators in general and particularly synchrotron light sources. The members of the group first took part in an initial training stage at the Joint Universities Accelerator School (JUAS), which was held for the first time near Geneva in Haute Savoie in 1993, and then went on to receive further training in various different centres abroad.

Following two years of funding by the Catalan government (including a geo-technical study on a potential location on the campus of the Universitat Autònoma de Barcelona (UAB) on land that the university was willing to cede), a Co-operation Agreement was signed in Madrid on 20 March 1995 between the Spanish Comisión Interministerial de Ciencia y Tecnología (CICYT) and the Catalan Comissió Interdepartamental de Recerca i Innovació Tecnològica (CIRIT) to set up and run the synchrotron laboratory, one of the purposes of which was to make a detailed three-year study of the project. The detailed study of the design of the synchrotron light source carried out during these years by this group[3], including construction of the most important prototypes by Spanish companies, was completed in December 1997 and published at the beginning of 1998.

This agreement has been renewed annually and has financed the cost of the work until now, with a total figure of EUR 1.8 million up to 2002. This was complemented by the accord of the Executive Council of the Generalitat de Catalunya on 2 May 2000 which set up the Laboratori de Llum de Sincrotró (LLS) consortium (Synchrotron Light Facility consortium) made up of the Generalitat de Catalunya and the Universitat Autònoma de Barcelona, the long-term objective of which was to “build a synchrotron light source”.

Interest in a synchrotron light facility in SW Europe was shared by all of the Spanish and French regions grouped together in the Comunitat de Treball dels Pirineus (CTP, Pyrenees Working Community) that was also active in promoting a synchrotron light facility in the area. After various specific meetings, it became clear that joint action was the best way of both promoting the construction of the SOLEIL synchrotron light facility in southern France and constructing a synchrotron source in Spain. These actions were made specific in the resolution signed by the Presidents of the Pyrenean regions in Ordino (Andorra) on 8 July 1999. The decision of the French government to finally construct the SOLEIL facility in Saclay near Paris increased the likelihood of a syn-

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[2] It was initially headed by the author of the article and later on by Joan Majó. An international Advisory Committee was simultaneously formed by the directors of large foreign facilities and chaired by Professor Manuel Cardona, which was constituted on 16 April 1993.

[3] Doctor Joan Bordas, who was an advisor to the working group, had meanwhile joined the project in September 1996 and taken over the role of director.

chrotron source in El Vallès being supported by the regions in the south of France, particularly following the signing of the agreement by the Spanish and French governments to work together in fields such as synchrotron light.

Once the detailed study of the project was completed, the then Ministerio de Educación y Ciencia commissioned an assessment by three foreign specialists and subsequently a specific report commission, headed by Doctor Rafael Abela from the Swiss Light Source (SLS) at the Paul Scherrer Institut, the third generation synchrotron light facility in Switzerland[4], was set up to evaluate the Spanish requirements in this matter. The commission's extensive report analysed the Spanish synchrotron light requirements and appraised different solutions put forward to cover the demand. It gave a clear recommendation for a synchrotron light facility to be built with the characteristics that had been designed in Barcelona. The study was reviewed by the Comisión de Grandes Instalaciones Científicas y Técnicas (Commission for Large Scientific-Technical Facilities), which also evaluated possible alternative solutions to fulfil the Spanish requirements with regard to synchrotron light. The commission made a unanimous priority recommendation in the summer of 2001 to build a synchrotron light source as proposed and to not delay the decision any longer.

The Consejo de Ministros (Council of Ministers) of the Spanish Government finally gave approval for the synchrotron light source project, which is to be built in the area of El Vallès, on 8 March 2002. A protocol of intentions was signed by the President of the Generalitat de Catalunya and the Spanish Minister of Science and Technology six days later on 14 March within the context of the European Council meeting in Barcelona under the chairmanship of the President of the Spanish Government. This protocol established the commitment to build, install and run a synchrotron light source in Cerdanyola del Vallès, and laid down the signing by the two Administrations of a specific agreement regulating the details of the project, which would be financed equally by the two promoting Administrations.

The definition of the legal structure of the large facility was then worked on and the formal setting up of the Consortium to build, install and run the Synchrotron Light Laboratory was finally signed by the Spanish Minister of Ciencia y Tecnología and the Catalan Minister for Universitats, Recerca i Societat de la Informació, in the presence of the President of the Generalitat de Catalunya, on 14 March 2003.

Figures for the cost and capital to be provided by the two Administrations have been defined and appear in Table 1. EUR 2,633,348 have been set aside in the budgets of both administrations to ensure the start of activities this year and both have approved the multiannual contributions to cover the economic forecast. It is anticipated that the Synchrotron Light Facility will be in operation by 2008.

A long maturity period for a large facilities project like this is not surprising. When the El Vallès project was

> **A long maturity period for a large facilities project like this is not surprising.**

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[4] See below, next page and table 5.

Table 1
Estimated cost and financial plan of the construction and installation of the Synchrotron Light Facility (in current EUR)

Year	2003	2004	2005	2006	2007	2008	TOTAL
MCyT	2.633.348	9.581.956	12.459.086	16.898.772	21.371.236	18.994.496	81.938.894
GdC	2.633.348	9.581.956	12.459.086	16.898.772	21.371.236	18.994.496	81.938.894
TOTAL	**5.266.696**	**19.163.912**	**24.918.172**	**33.797.544**	**42.742.472**	**37.988.992**	**163.877.788**

begun in 1992, four other synchrotron light sources were being planned in Europe, namely ANKA in Karlsruhe, the Swiss Light Source (SLS) in Villingen, near Zurich, SOLEIL in France and DIAMOND in the UK. At the present time, only two of these are up and running and they have only been put into operation recently. A 5-milliampere current with an energy of 2.5 GeV[5] was produced at ANKA in March 2000, the final adjustments to the beamlines made in December 2001 and synchrotron light supplied to users in December 2002. The SLS was officially inaugurated on 19 October 2001. Permission to construct SOLEIL was only given on 6 November 2002 by the Saint-Aubin municipality near Paris and the construction of DIAMOND began in Chilton near Oxford on 27 March 2003.

Section 2 sets out the need for a synchrotron light facility in Catalonia, Spain and SW Europe and the different reasons for building one. Section 3 explains what synchrotron light is and how it is produced. Section 4 gives an explanation of the most important uses of synchrotron light. The potential impact and spin-off from the synchrotron light facility in the El Vallès area are described in section 5, and section 6 gives various details about the project and the current situation.

2. The need for synchrotron light in Catalonia, Spain and SW Europe

Evidence of the use and need for synchrotron light for the progress of science is the rapid increase in the number of new light sources that are in operation or being built or planned around the world. Many countries have consequently built national third-generation synchrotron sources of advanced specifications either as new facilities or to replace existing ones, as is the case with Germany, France, Italy, United Kingdom, Switzerland and Sweden in Europe, United States, Japan and Russia. The situation is similar in other countries where new light sources are being built, such as Armenia, Australia, Canada, Jordan, Thailand and Ukraine and other countries where they exist, such as Brazil, South Korea, Denmark, India, Taiwan, and China.

Aside from these light sources in different countries, in certain cases there is a need for synchrotron light with characteristics that exceed the capacity of the above-mentioned local light sources. This is the reason why Europe, USA and Japan have built complementary light sources at a cost that would be unacceptable to individual countries with a more reduced

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[5] An electronvolt is the energy acquired by an electron when it accelerates in a vacuum through a potential difference of 1 volt. Its symbol is eV. Its value is 1eV = 1.60×10^{-19} Joules. A giga electronvolt (GeV) is equivalent to one thousand million eV.

economic potential, and can thereby supply top-quality radiation for highly specific experiments. The first of these was the European light source at Grenoble (the above-mentioned ESRF, in which Spain has a 4% participation). The Japanese SPring-8 source in Nishi-Harima was recently put into operation, as was the Advanced Photon Source (APS) in Argonne, Illinois (USA).

As with the field of accelerators in general, neither Catalonia nor Spain has played an important role in the development of synchrotron light sources up until the present time although there is a considerable number of Catalan and Spanish scientists who are currently involved in the scientific use of synchrotron light sources abroad. Table 2 shows the number of Spanish groups that used foreign synchrotron light sources in the period 1995-2000 (excluding the ESRF), either through joint scientific projects, personal contact or by way of European Union access programmes to large facilities[6].

An analysis of the demand from the Spanish scientific community carried out as part of the El Vallès Synchrotron Light Facility project showed[7] that there were more than eighty groups in Spain (involving more than six hundred scientists) at that time interested in synchrotron light. As can be seen from figure 1, the majority needed intense light in the X-ray energy region[8] between 4,000 and 30,000 eV and high brilliance light in the X-ray energy region between 100 and 2,000 eV. It was clear from these figures that Spain needed a third generation synchrotron light source with insertion devices (ID), undulators to generate high brilliance light in the region of soft X-rays and wigglers that produce intense light in the region of hard X-rays[9].

Table 2
The number of Spanish groups using synchrotron light sources abroad (excluding the ESRF) in the period 1995-2000

FACILITY	**GRUPS**
BESSY (Germany)	11
HASYLAB (Germany)	6
ELETTRA (Italy)	4
LURE (France)	17
SRS (United Kingdom)	15
Max-Lab (Sweden)	2
ALS (USA)	2
SRC (USA)	2
NSLS (USA)	2
Spring8 (Japan)	1
Photon Factory (Japan)	2
TOTAL	**64**

According to the Abela report mentioned above, the number of groups identified in 2000 had already increased to 159 all around Spain, 90% of which were interested in the X-ray band of the spectrum. The conclusion of the report was that the needs of the Spanish community of users of synchrotron light was not covered sufficiently by foreign light source facili-

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[6] From the Abela Commission report “Una Fuente de Luz Sincrotrón en España”; Madrid, 26 February 2001.

[7] J. Campmany, Investigación y Ciencia no. 239, August 1996, p. 82-83.

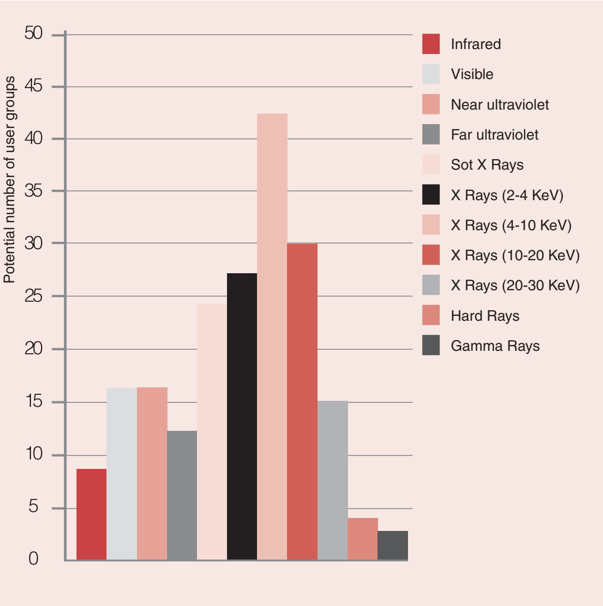
[8] Light is characterised by a wavelength λ and frequency ν, the latter being related to the wavelength through the equation $c = \lambda\nu$, where c is the speed of light in vacuum. Likewise, the characterístics of light are sometimes referred to by the energy E of its photons, which is related to the frequency by $E=h\nu$, where h is Planck’s constant. Given the values of c and h, visible light with a wavelength of 300 nm corresponds to a frequency of 1015 Hz (1 Hz = 1 s^{-1}) and its photons will have energies of 4.1 eV.

[9] IDs, wigglers and undulators are devices with a periodic magnetic field that is designed to make the electron beam follow a sinusoidal path, which produces the emission of light. Due to their special geometry, they increase the brilliance by several orders of magnitude over that emitted by bending magnets.

ties and that, of the European countries without a light source, Spain had the largest number of user groups, which limited the work of these groups and the setting up of new groups and new lines of work.

Apart from circumstantial access by certain Spanish users to other sources abroad, the CSIC has a line specialised in photoemission techniques at the French synchrotron light laboratory (LURE) in Paris. Access to public beamlines is available to Catalan and Spanish users (as for all participating countries) at the ESRF, where there are also lines belonging to different entities and countries. Through an agreement between the CICYT and CIRIT, Spanish users had their own beamline (BM14) during 2001 and 2002 that specialised fundamentally in macromolecular crystallography and the study of anomalous dispersion. As of 2003 and for a period of five years, the agreement provides Spanish users with a different beamline (BM16) of similar characteristics (they no longer have the previous one). Spain is also constructing the SpLine, which is another beamline in the same installation that will soon come into operation.

Figure 1
Potential number of user groups in Spain according to their needs



This current and anticipated capacity is, and will be, insufficient to cover the requirements of scientific development in Spain, which has to compete on an international level. On the one hand, the capacity of the ERSF can only admit a proportion of the Spanish users needing photons in the normal and hard X-ray region and, on the other, the high energy (6 GeV) and the special scientific characteristics of the ERSF do not allow for the installation of insertion devices (ID) optimised for the soft X-ray region nor for lower energy ones that are required for many needs of the community of users.

Spain and other countries that are building or planning new sources already have access to international facilities so the inevitable question is why set up so many sources when the existing ones could be shared? Aside from the technological and strategic interest of the facilities, the number of insertion devices needs to be increased to meet the demand for optimised radiation, which in turn increases the size of the accelerator and its cost. Given that this increases with the surface area and not with the perimeter of the accelerator, there is no saving in investment in building and sharing a very large accelerator. Moreover, an excessive increase in the size of the ring reduces the curvature and, unless there is an excessive increase of energy, less radiation is emitted by the dipoles and the capacity for installing many experimental stations is reduced. For example, the volume of use of the ESRF is no higher than that of other national facilities that are smaller and of smaller energy. An additional factor is that the costs of running a foreign facility are higher than those of a national source.

Other strategic considerations, connected with a country's need to create its own practical knowledge and know-how and to thereby have influence over an extensive area with regard to the process of creating wealth, make the choice of sharing a source undesirable. For example, synchrotron light techniques are regularly applied by large companies in quality analysis and manufacturing processes. Companies need know-how that can only be generated in a national facility with wide-ranging scientific objectives before making full use of a synchrotron light source. It would be extremely difficult, if not impossible, to generate and maintain this knowledge through access to a foreign synchrotron source.

3 Synchrotron light and how it is produced

According to Maxwell's laws of electromagnetism, an electrically-charged particle that is speeded up (or slowed down) emits electromagnetic waves in a continuous spectrum and when a particle moves at velocities approaching the speed of light, as occurs in synchrotrons, this radiation has unique properties that are highly interesting for a wide range of scientific activities. Synchrotron light is the radiation emitted by a charged particle, usually an electron, at a bend in the trajectory at velocities approaching the speed of light, as occurs in a synchrotron[10].

The unique properties of this form of radiation make it highly interesting for a wide range of scientists. A large dipole magnet bends the high-energy beam of electrons in a synchrotron and this centripetal acceleration produces a continuous fan-shaped beam of synchrotron light tangential to the curve of the particle beam as long as the flow of electrons is maintained. Light is emitted forward in a tangential direction to form a highly collimated beam[11] in a cone with a spread of around a few dozen microradians. This light is much more intense than that of conventional sources[12] and it extends over a continuous spectrum from infrared to X-rays; it is polarised in the orbital plane and moreover is emitted in extremely short pulses (typically several picoseconds in length) and with a periodic structure (in microseconds).

Following the first experimental demonstration of the use of synchrotron light at the National Bureau of Standards accelerator in the USA in 1963, just 40 years ago, the initial so-called 'first generation' experiments were carried out using synchrotron light emitted by bending magnets in high energy particle physics accelerators. By adapting traditional laboratory techniques, high quality results were obtained. Later on, second-generation synchrotrons were built and optimised solely for their ability to generate synchrotron radiation. The first (known as Tantalus) was built at the Synchrotron Radiation Centre at the University of Wisconsin (USA) in 1977. The first source in Europe was launched in Daresbury (UK) in 1978. The number of synchrotron light sources at the present time has increased considerably.

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[10] The emission of synchrotron light also takes place in stellar systems where electrons fall on stars, moving through a spiral trajectory as they do so.

[11] That is, confined to an extremely narrow spread.

[12] In terms of photon flux (the number of photons per square millimetre and per second) and in different wavelengths, medical X-ray equipment emits around 10 million photons; a candle around a thousand million; sunlight around 10 billion and a synchrotron light source around 10 trillion.

The history of particle accelerators

Accelerators are used to obtain high resolution probes and they consist of devices that are capable of electromagnetically accelerating particles. The particles therefore need to be electrically charged and generally to be stable during the acceleration process [1], as with electrons, protons and ions (or their respective anti-particles, if a sufficiently high vacuum can be used to prevent their annihilation as they crash into their corresponding particles in the residual gas).

Aside from electronic microscopes, which are true accelerators with a limit to their maximum energies of a few hundred keV, the first particle accelerators consisted of ingenious devices used to obtain high differences of electrical potential. John D. Cockcroft (1897-1967) and Ernest T.S. Walton (1904-1995), who were working in the United Kingdom in 1929, accelerated protons that, on being slammed into a target of lithium-7 produced two nuclei of helium. Robert J. Van de Graaff (1901-1967) constructed the accelerator named after him in the United States in1933. These electrostatic high voltage generators accelerate charged particles with a weak energy dispersion and a continuous current. The high voltage necessary, as with electronic microscopes, was limited by discharge phenomena. These accelerators were used to obtain energies higher than those provided by natural radioactive sources that were used in the initial experiments on nuclear physics, such as those by Ernest Rutherford (1871-1937), which enabled the existence of atomic nuclei to be identified. The primitive particle accelerators also had advantages over cosmic rays that have much higher energies but reach the Earth in a random way.

The limitations of these accelerators were overcome with the use of a variable electrical field that acts various times on the particle trajectory. In the case of rectilinear trajectories, a linear accelerator is used with a pulsed beam. The first was built in 1932 and it was used to accelerate protons up to 1.26 MeV. A larger number of accelerator units along the trajectory were used to increase the energy, which led to accelerators becoming increasingly bigger. The most powerful linear accelerator ever built is the one in Stanford, which is around 3 km long. A higher number of accelerator units obviously proportionally increases the cost of the accelerator.

The first circular accelerators appeared almost at the same time. The principle with this type of accelerator consists of sending the charged particles around a circular trajectory using uniform and constant magnetic fields perpendicular to the plane of the trajectory and, at certain points along this, an accelerated potential difference is applied. The radius of curvature of the trajectory increases with the velocity of the particle, which follows increasingly larger trajectories similar to a spiral as it accelerates. The first circular accelerator was the cyclotron built by Ernest O. Lawrence (1901-1958) in Berkeley in 1930. It was a small flat vacuum cylinder divided diametrically into two semicircles subjected to a uniform magnetic field along the axis of the cylinder. An electrical potential difference was set up between the two half-circles of the disk. Charged particles injected into the gap near the centre are pulled by the potential into one of the electrodes, which are then bent in a semicircle back into the gap; in the meantime the electric field has reversed and can pull them into the other semidisk; whence they emerge again in step with the electric field; and so on, eventually spiralling out to the edge. Each passage through the gap boosts the particles to higher energies until the radius of the last semicircle travelled reaches the value of the full radius of the disk, which is when the particle beam is removed using an electrical field. The energy of cyclotrons was no greater than a small fraction of the rest energy of the particle, especially because of the limited size of the disk subjected to the uniform magnetic field. Although cyclotrons are still used extensively in the field of medicine, the need for higher energies led to them being developed, via the betatron, the synchrocyclotron and the isochronic cyclotron, into the synchrotron, which was proposed in 1945.

The idea of synchrotrons is not for the beam of particles to travel trajectories of different radii but to always follow the same more or less circular trajectory in a vacuum

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[1] Apart from accelerating electrons and protons and their anti-particles, thought is currently being given to accelerating muons, which only have a half-life of two millionths of a second but when moved at high speeds, the relativistic dilation of time enables the entire process of acceleration to take place.

tube, driven by dipole bending and other magnets that help to focus the beam. As the energy increases, the intensity of the magnets is regulated so that they adjust to the velocity of the beam at all times so that the radius of curvature of the trajectory does not change. The particles are injected with a relatively low energy (often from a small linear accelerator) that is increased by accelerator radiofrequency cavities installed at points on the trajectory. The repeated passing through the accelerator cavities progressively increases the energy of the beam to speeds that can almost reach the speed of light if the magnets are strong enough. The first synchrotrons were the Cosmotron in Brookhaven and the Bevatron in Berkeley, which were built at the beginning of the 1950s and accelerated protons up to 3 and 6 GeV respectively. The first to achieve a highly focused beam was the Proton Synchrotron (PS) at CERN (European Particle Physics Laboratory) in Geneva in 1959, which produced protons of 25 GeV. The most powerful synchrotrons that have been built are the SPS (450 GeV) at CERN (protons), the one at Fermilab (800 GeV, protons), near Chicago, which uses superconducting magnets, and now the CERN accelerator complex, with the Large Electron Positron (LEP), which is currently out of service for the construction of the Large Hadron Collider (LHC) in its 27 km long tunnel[2], the completion of which is anticipated in 2007.

The increasing energy of accelerators plays an important role in determining their cost and a balance has to be found between energy and size/price. The cost of linear accelerators is determined by the number of accelerator cavities positioned along the trajectory and which the projectiles pass by just once. In synchrotrons, on the other hand, the particles pass by each cavity many times, which would appear to make them more economical, despite the considerable cost of the bending magnets that force the particles to follow a circular trajectory. There is another factor that determines the cost, however, which has to do with the fact that according to classical electromagnetism, each charged particle subjected to acceleration emits energy at a rate of loss that is proportional to the square of the acceleration.

The particles in synchrotrons are accelerated in a centripetal way, no matter how large the radius of the trajectory curvature and they therefore emit (lose) more energy when a synchrotron is smaller. This energy “loss”, which is larger when the particle is lighter, is what is known as synchrotron light and was observed for the first time in 1947. Therefore, in order to obtain a certain energy for a particular particle, a balance needs to be found between a large accelerator, which is more expensive but has less curvature and fewer losses, and a small cheaper one with a higher consumption. This is why high energy physicists interested in obtaining higher energies at a lower cost built the 27 km circumference LEP to reduce synchrotron radiation and also why they think that the next large electron accelerator - with more energy - will need to be linear. On the other hand, those who are interested in using synchrotron light are interested not in reducing these losses but in maximising them and they will therefore make synchrotrons that are comparatively smaller.

It is nuclear and particle physics that has set the leading edge with regard to the largest energy accelerators and the concept of storage rings has been introduced, where particles circulate at constant energies for long periods of time, either to experiment head-on collisions as in colliders or to emit synchrotron light. The first collider to be built in the field of particle physics was the so-called Intersecting Storage Ring (ISR) at CERN. The Super Proton Synchrotron (SPS), also at CERN, was later on made to produce collisions of protons with anti-protons in the famous experiment where intermediary Z and W bosons were discovered. The largest proton collider that exists at the present time is the one at Fermilab, which reaches energies of 1800 GeV (the maximum obtained), which enabled the quark top to be discovered. The most important electron-positron colliders are the ones built at DESY in Hamburg, which currently operates by making electrons (of 30 GeV) collide with protons (of 800 GeV) and is known as HERA; the SLC, which feeds off of the SLAC linear accelerator; and the above-mentioned LEP at CERN, which was the largest electron and positron collider in the world (since 1989) and enabled large quan-

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[2] Unlike other synchrotrons, LEP is underground as a result of its size.

tities of intermediary W and Z bosons to be created. LEP was closed down in November 2000 after having been run for two years at an energy close to 100 GeV per beam, which enabled pairs of W bosons to be created. The new large collider under construction is the LHC (also mentioned above) at CERN, which is expected to reach 7000 GeV of energy per beam.

Leaving to one side these large accelerators of high-energy physics at the leading edge with regard to the energy, the applications to which accelerators are put are highly diverse. Aside from the applications related to synchrotron light that have already been mentioned above, some of the most important include the world of medicine, where at the beginning of the 1940s radiation began to be used as a therapy and by the 1960s the medical applications of the cyclotron to produce radio-isotopes began to increase; later on, accelerators began to be used in positron emission tomography (PET) and in the use of hadron beam and heavy particle therapies. Accelerators are also used in the world of art and archaeology, where works of art can be analysed. A painting in the Louvre attributed to Pisanello (1395-1455) was shown to be false due to the low copper content of the pigment, which was determined by using the PIXE technique of the “Great Louvre Accelerator”; and the Pazyryk carpet at the Hermitage, the oldest one known in the world, was dated at being from 250 BC as a result of radiocarbon techniques carried out at ETH/PSI in Zurich.

Synchrotron light can also be used to test whether a document or bank note is original or false. Infrared spectromicroscopy enables the quality of ink to be studied with an unprecedented sensitivity and can characterise sweat samples in a way that makes them as unique as fingerprints. Some of these techniques are not new but they used to require a large sample. Although the necessary size has decreased over the years, synchrotron light today enables samples of merely 10 microns or less to be used, without the need to handle or destroy them and with much greater precision as a result of the high intensity of modern synchrotron light sources.

Extensive use is made of accelerators around the world and there are approximately 15,000 in total (70 of which are synchrotron light sources). Table 1 shows their distribution according to fields of use. Up until the present time in Spain, there have been several used in the field of medicine, various ion implanters, a tandem 3 MV ion accelerator at the Centro National de Aceleradores at the Universidad de Sevilla and a 5 MV maximum voltage ion accelerator at the Centro de Micro-Análisis de Materiales at the Universitat Autònoma de Madrid, all of which were purchased on a turnkey basis. Furthermore, the small number of different types of accelerator in Spain also resulted in a lack of experts in the field as well as in some of the associated technologies until very recently.

Main types of accelerator in the world according to field of use (approximate figures)

Type	Number
Ion implanters and surface treatments	7.000
Industry	1.500
Non-nuclear research	1.000
Radiotherapy	5.000
Production of medical isotopes	200
Hadron therapy	20
Synchrotron light sources	70
Nuclear and particles research	110
TOTAL	**14.900**

The electrons in a synchrotron light source travel in bunches of 10^9 electrons that circulate around the ring in an ultrahigh vacuum chamber. These bunches are very small in size and the beam is made up of various bunches. While the electrons mutually repulse each other electrostatically inside the bunches, this effect is not so important at relativistic velocities and the bunches can be kept at a very small volume. Another effect to be considered is that the vacuum chamber is made of metal and each bunch induces an electromagnetic field that disturbs the movement of other bunches following behind. The effect is similar to the vibration felt on a boat that follows in the wake of another; as in this case, the particles vibrate as a group with a amplitude that increases in time and these oscillations therefore need to be minimised and controlled.

Dipole magnets bend the high-energy beam of electrons in a synchrotron and the centripetal acceleration produces a beam of synchrotron light (beamline) tangential to the curve of the particle beam that passes through a monochromator, which selects the required wavelength for a particular experiment and, by way of a series of mirrors, focuses it on the sample to be examined. The light is picked up by a sensor, which sends the data to a data acquisition system where they are saved and processed.

Synchrotron light sources are characterised by so-called critical energy, E_C which is an energy such that half of the entire radiated power is emitted at photon energies above the critical value and half below the critical value (E_C)[13]. Given the sensitivity of modern-day sensors, photons are useful up to energies of around 2.5 times E_C. One or more experimental stations that use synchrotron light are set up at each bending magnet. The quality of the light emitted is given by the spectral flux[14] and brilliance[15].

The high flux and brilliance of synchrotron light and the continuous spectrum of wavelengths, which enables researchers to be able to select the wavelength required (which make it unique for many applications, as described below), are complemented by the polarisation of the emitted radiation, which provides for many applications, for example differentiation of the symmetry of electronic states, and their temporary structure, which enables real time dynamic studies to be carried out with a resolution down to one thousand millionth of a second.

In third-generation synchrotron light sources, electrons[16] are fed from a small linear accelerator at energies of around 200 MeV into a booster ring that accelerates them to nominal energy, which is often around 2.5 or 3 GeV, corresponding to a velocity of 99.999% of the speed of light in vacuum. On leaving the booster, a deviator magnet feeds them into a storage ring where a series of magnets[17] with a large magnetic field keep them circulating for hours until a large part have been lost, at which point more electrons are reinjected. Alternatively, in what is known as top-up injection, continuous refilling of beam-current maintains them at an approximately constant intensity. This type of storage ring has a polygonal form with alternating curved sections with dipole magnets in the vertices of the polygon that bend the trajectory and straight sections where electrons travel freely in a straight line. Charged radio frequency cavities are used on certain straight sections to accelerate and restore the lost energy of electrons due to the emission of synchrotron light.

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[13] Its value is $E_C=0.665\ BE^2$, where E_C is expressed in thousands of eV (keV), B is the magnetic field in tesla (unit of the field of magnetic induction that corrresponds to around twenty thousand times the magnetic field of the Earth) and E is the energy of the particle in GeV.

[14] Spectral flux is the number of photons per unit of time, per horizontal angular aperture and for a given percentage of bandwidth; measured in photons/s/mrad/0.1%BW.

[15] Spectral brilliance is the number of photons per second, per unit of area, per unit of solid angle in a given bandwidth; measured in photons/s/mm^2/mrad^2/0.1%BW. An acceptable level of brilliance in these units would be higher than 10^{14}.

[16] The drawback with positrons, which have the same rest mass as electrons, is that they are more difficult to produce and, above all, maintain before they get anhiliated with residual electrons in the vacuum chambers where they move; on the other hand, they have the advantage that they reject residual positive ions in the chamber because of their positive charge; up until now, however, they have not been used to produce synchrotron light.

[17] As well as dipole (or bending) magnets, which bend the trajectory of the electrons, synchrotrons also have quadrupole magnets that focus the electrons so they stay in their orbit and sextupole magnets that reduce energy dispersion by slowing down the fast electrons and accelerating the slow ones so that they all travel at the same speed. Other magnetic systems have other specific missions.

One of the most important characteristics of modern synchrotron light sources is that the length of the straight sections between the bending magnets is increased by several metres to install insertion devices (ID, wigglers and undulators), which are instruments that produce higher quality light than bending magnets[18].

A wiggler generates a high intensity of photons by adding the radiation emitted by each of its poles. Moreover, it has a higher magnetic field than bending magnets[19] so the energy range of the photons can be increased. An undulator has a lower magnetic field so that the angular excursion of the electrons is lower than the natural cone angle of emission of synchrotron light. This produces constructive interference that redistributes the soft spectrum of the synchrotron light into a series of intense high harmonics compressed into a cone angle of just a few microradians. In other words, an undulator increases both the intensity of the photon beam (although at lower energies than a wiggler) and the degree of collimation and, therefore, its brilliance.

4. Uses of synchrotron light

Synchrotron light is currently being used more and more in numerous fields of industrial research and especially basic research. Up until the 1960s, the main and almost sole users of synchrotron light were physicists who made what could almost be qualified as parasitic collateral use of light emitted by synchrotrons in nuclear and particle physics laboratories. Since then, however, the situation has changed; numerous synchrotron light sources have been built specifically for this purpose and many new applications based on a wide variety of techniques have been made and while it is scientists in certain fields of biology who are today becoming one of the main group of users around the world, easy access to a synchrotron light source is now highly important in many fields of competitive research in both the public and private sectors.

Important industrial users of synchrotron light include the pharmaceutical industry, which uses it to design new medicines; the food industries, which use it to improve the properties of their products; cosmetics manufacturers interested in product effectiveness and eliminating counter-productive side-effects; different sectors in the textile industry interested in producing new synthetic fibres; enterprises interested in catalysts and pollution problems; etc. Other uses include the traditional use of lithographic techniques used in microelectronics and nowadays micromechanics, where innovative LIGA techniques have led to the ANKA source being put into operation in Karlsrhue, which is used mainly for the micromanufacturing of devices used in a wide range of fields including medical implants and microsurgery. The list is almost endless and the number of applications continues to grow; companies that actually benefit from all of this, however, are those that make large investments in R+D to ensure their competitiveness.

A description is given below of several areas in which synchrotron light is applied in fundamental and applied research in fields as diverse as physics, chemistry, materials science, structural biology, geophysics, environmental physics, etc.

There are many important fields in physics that require synchrotron light. These include the study of

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[18] See note 9, p. 86.

[19] Superconducting electromagnets are sometimes used.

magnetic phenomena at the microscopic level, with important applications in the development of data storage products; the spatial determination and variation of the atomic and electronic structures of many materials and analysis of the effects of high pressure and temperatures on structure; high resolution determination of the structure of superconducting materials; the study of the behaviour of materials at critical interfaces between gaseous, liquid and solid phases. Synchrotron light has been crucial in many advances made in surface science techniques and it continues to be so from the applied perspective, for example, in the study of surface phenomena involving corrosion, surface doping, the surface engineering of disposable products, electrochemical alterations, hydrophobic coatings, adhesives, etc.

One spectacular example of the power of synchrotron light is how the study methods of the atomic structure of biological systems using biological macromolecule crystals have been transformed.

There are many substances in materials science that are totally or partially non-crystalline. In certain cases, their properties are connected with the presence of nanocrystals or chemical impurities. One area in which particular success has been achieved with synchrotron light has been the progress made in determining the local atomic structure of disordered materials, from glass to semiconductor impurities. Many advances have been made in magnetism, such as soft X-ray magnetic circular dichroism techniques exclusive to synchrotron light that offer unique possibilities, the field of sensors, which is an increasingly important market, the detection of in situ magnetic microstructures, etc.

The use and applications of synchrotron light in the fields of the life sciences and biochemistry have increased even more. For example, synchrotron light permits the study of conformational changes in dissolved biological macromolecules through the use of temporary resolution X-ray dispersion techniques, given the unique temporary structure of synchrotron light. The techniques are similar to conventional spectroscopic techniques with the fundamental difference that they can also provide direct structural information at the molecular level at the same time. As the intensity of the dispersed signal is very weak and high resolution is necessary, these methods can only be applied by using synchrotron light sources. Temporary resolutions above a millisecond open up the possibility of systematically studying the structural dynamics of, for example, the structural cynetics of protein folding. Another field that is opening up is that of biological complexes that form bi-dimensional structures such as membranes; low angle X-ray diffraction experiments provide direct information on the structural dynamics of how these complexes work, for example, when they transport ions or small molecules through a membrane. This is also the case with the study of the structural dynamics of other fibrous molecules, such as DNA and muscle tissue.

One spectacular example of the power of synchrotron light is how the study methods of the atomic structure of biological systems using biological macromolecule crystals have been transformed. The resolution of a structure used to require years of work whereas synchrotron light techniques enable this to be done in an almost routine way in a question of hours. Now that the Human Genome Project has been completed, this important advance enables the next great scientific challenge to be realistically handled, namely determining the structure of the tens of thousands of proteins coded by the genome. This discipline, which is now known as proteomics, may well become one of the great breakthroughs of the Twentieth-first century and synchrotron light is one of the central tools that will be essential for its success.

Another example is the progress made in determining the immediate environment of metallic centres in biological macromolecules made possible through the use of spectroscopic X-ray techniques that can only be applied in synchrotron light sources. Metals are involved in reactions as diverse as DNA transcription, photosynthesis and many enzymatic mechanisms. These techniques enable the structure around a metal centre to be determined down to a precision of around 0.002nm and in principle these methods can also be used to determine changes in the local chemistry of metal centres during a biochemical reaction.

There is a certain number of emerging techniques, such as magnetic circular dichroism (with or without temporary resolution), confocal microscopy, point spectroscopy, or experiments on temporary and spatial correlation using coherent X-ray dispersion, that have enormous potential in the study of the structure and function of biological systems. While some of these techniques are at the incipient level, it is probable that they will soon become routine applications.

Certain applications of synchrotron light in medicine are also under consideration, such as the field of coronary angiographies, and new fields of application are constantly arising in highly diverse sectors. A recent application of infrared synchrotron light at the Advanced Light Source in Berkeley, for example, enables samples smaller than 10 microns to be non-destructively analysed in order to detect, amongst other things, whether a document or bank note is false or has been tampered with.

Table 3 gives a summary of the main characterisation techniques that use synchrotron light sources, the areas of application and the fields of science and industries where they are used. Techniques that alter the state of samples are given in table 4.

The wide diversity of fields of application and analytical techniques made available by synchrotron light, of which a mere brief summary is given here, is undeniable proof of the importance of synchrotron light sources in a great variety of fundamental and multidisciplinary scientific fields.

5. The impact of a synchrotron light facility

A synchrotron light source, as with any large scientific-technical facility, has a big impact on its surroundings, both in scientific and technical as well as economic and social terms. The scientific and technical impacts are the direct consequence of the wide possibilities opened up by synchrotron light sources for the scientific community and enterprises that use them to carry out research and innovation. Aside from this intrinsic interest, however, large facilities are also tools that stimulate the technological development of a region and it is in the surrounding area where a process of cross-fertilisation between research, development and industrial innovation takes place, resulting in the actual transfer of knowledge to enterprise. Technological enterprises frequently locate around large facilities and jointly participate in the design and manufacture of prototypes together with personnel from the facility, partly to cater for their own needs for instrumentation and equipment that are not available on the market. In the process, they acquire technology that can then be applied to other commercial products and thereby optimise the investment made in constructing the prototypes. Such collaborations are not just limited to the time of the initial investment due

Table 3
Main characterisation techniques and the areas of science and technology where they are applied

Techniques	Applications	Fields of science and industries
Absorption spectroscopy	Density, atomic environment, chemical composition, presence of low concentrations (< 10 ppm), study of metallo-organic compounds	Petrochemicals, environmental control, catalysis, pharmacy, new materials
Diffractometry	Low concentrations and small monocrystals, polymeric and protein structures, fine crystalline structures, minority phase studies, stress and strain, amorphous and vitreous materials	Pharmacy, analytical chemistry, nutrition, metallurgy, aerospace iindustry, plastics
Fluorescence and photoelectron spectroscopy	Electronic levels, bond energy, trace analysis, catalysis, corrosion	Surfaces, solutions, fine chemistry, metallurgy
Protein crystallography	Polymorphism distinction, viral structures	Medicine, pharmacy
Dispersion	Ordered materials, interfaces, structures in homogeneous media	Pharmacy, fine chemistry, paint, food, polymer processing, electrochemistry, cosmetics
Chemical topography, tomography	Tests for quality	Electronics
Radiography	Strain, textures, morphology and defects in materials, angiography, mammography	Medicine, aeronautics, metallurgy
Confocal microscopy	Drug specificity and their action on living cells	Pharmacy, cosmetics
Infrared	Optical properties and chemical analysis	Chemical analysis

Source: Abela Report

Table 4
Main techniques that alter the state of samples and the fields of science and industries where they are applied

Techniques	Applications	Fields of science and industries
Hard X-ray lithography	Microcomponent manufacture using LIGA technique	Micromechanics
Soft X-ray and VUV lithography	Chip manufacture	Microelectronics
Monochromatic illumination	Photon-activated processes	Catalysis, chemical synthesis

Source: Abela Report

to the fact that large facilities always have maintenance and updating programmes that often last their entire lifespan, which in the case of a synchrotron light source is at least more than thirty years.

During the initial stage, large facilities also lead to the development of construction technologies as the result of non-standard building characteristics that are required of construction firms. In the case of a synchrotron light facility, for example, highly demanding requirements are made of the building with regard to ground stability, the insulation of a wide range of vibration frequencies (all frequencies exceeding amplitudes of a few micrometers in the band between 1 and 100 Hz), the insulation of electromagnetic fields, highly stable temperature conditions, etc.

Apart from civil engineering companies, the types of enterprise that benefit in this way from synchrotron light sources mainly include manufacturers of high precision (usually one part in 10,000), permanent and non-permanent magnetic systems; manufacturers of high output and highly stable power supplies (hundreds of kW); specialist firms producing ultrahigh vacuum systems (of the order of 10^{-10} millibar), precision mechanics and cooling systems; manufacturers of electronic systems and radiofrequency power systems (of the order of MW to frequencies of 100 MHz); numerous manufacturers of instruments for the accelerators, beamlines and insertion devices, diagnosis systems, optical systems of different wavelengths from visible to X-rays, etc. Extremely high demands are also made on computer firms (software and hardware) and those dealing with data acquisition and management.

One of the objectives of the synchrotron light source is to stimulate enterprises in the surrounding area. Studies that have been carried out indicate that, while Catalan and Spanish enterprises are still lacking certain technologies that are necessary in order to participate in the construction of the light source, these technologies can be obtained without too much effort and it is anticipated that around 70% of the supply and investment will be covered by Spanish enterprises. As explained below, this type of cross-fertilisation has already occurred in the case of enterprises that have participated in developing prototypes built during the design stage of the facility, to the point that all of them have been built by Spanish enterprises.

This scientific-technical impact ultimately results in a series of economic impacts, of which the most direct ones can be quantified. In the first place, there is an initial investment of around EUR 163 million and operating expenses that usually come to around 10% of the investment in the case of large facilities. Over one hundred jobs are created directly, most of which are for qualified personnel in different fields, to which one must add jobs that are indirectly created during construction and others that become included as the facility increases its capacity through the addition of new beamlines required by new users. The other main economic factor, which derives from a large facility as a centre of attraction for enterprises and new technological investment, is more difficult to quantify but is undoubtedly important.

Aside from the importance of the economic impact that the investment and job creation represent, synchrotron light sources are facilities that fundamentally specialise in providing a service to users. In the case of a synchrotron light source with the characteristics of the one being constructed in Catalonia, the annual figure just for the number of users of the five working beamlines initially programmed[20] would already be around a thousand. This figure will increase as the facility is completed and increased. The majority of users will not reside in the local area, which will generate a certain volume of business in the environs. Furthermore, the fact that researchers have a working instrument in synchrotron light will encourage the best researchers to stay and work here.

The presence of permanent and temporary qualified personnel in the facility itself and in enterprises that set up around it result in a positive social impact on the area surrounding a large facility, which in the case of El Vallès will make an important contribution to the social and urban environment, the core of which consists of the Universitat Autònoma de

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[20] See below, table 8.

Barcelona and the Parc Tecnològic del Vallès (Vallès Technology Park), which is served by the A-6 (from Barcelona to Madrid, and La Junquera on the French border) and C-58 national motorways (from Barcelona to France via Puigcerdà) and the B-30 highway, which runs parallel to the A-6, together with the new, recently approved Centre Direccional (development plan).

A large facility like this is also extremely important as far as personnel training is concerned. Due to its characteristics, a synchrotron light source requires a large number of personnel to be trained at the post-graduate and post-doctorate levels. Work in a centre that is characterised by the massive use of leading-edge technologies is one of the best places where professionals-to-be can acquire the training that will enable them to become qualified to work in a very wide variety of different environments in the future.

6. The Synchrotron Light Source project and its current situation

As mentioned above, one of the main objectives of the synchrotron light source project is to have a large accelerator facility, which in Catalonia has certainly been lacking. While Spain is a member of CERN and the ESRF, both of which are accelerator-based laboratories, and there are teams of high energy physicists in Catalonia and other Autonomous Regional Communities who are experts in elementary particle detectors as well as synchrotron light users, there is an insufficient number of experts working in a field as wide as that of accelerators. The project therefore has the fundamental objective of adding Catalonia and Spain to the list of countries that are most advanced in the use of synchrotron light and associated technologies and of making a synchrotron light source directly available to the scientific community in Catalonia and Spain. The purpose is also to have a large laboratory of excellence of international scope that serves as a personnel-training centre and to attract technological enterprises. A further objective is to establish a centre where the academic and industrial worlds can collaborate together and that also facilitates relations between basic research and development.

Large facilities like this need to be built preferably in areas that have good communications and are well connected and, if possible, that already have a certain scientific and industrial potential like that mentioned above. In this respect, a location near to Barcelona would appear to be an ideal location and El Vallès, with its extensive communications network, a short distance from and with good connections to Barcelona airport, is difficult to improve on. Furthermore, the recently approved new development plan (Centre Direccional), with a surface area of 340 hectares, will result in an investment of EUR 176 million as well as creating thousands of jobs. All of this forms the ideal location for the synchrotron light source facility.

The characteristics of this synchrotron light source will be similar to those of other recently constructed European sources or that are currently being built, as can be seen from table 5. It consists of an electron accelerator with conventional magnets forming a ring of approximately 250 metres in circumference. Electrons are brought to an energy level of several hundred MeV using a commercial linear accelerator. A synchrotron then accelerates the bunches of electrons to a nominal energy level of 2.5 GeV and they are then injected into the main ring where they circulate at a velocity close to the speed of light. Electrons emit synchrotron light in this ring where radio frequency cavities are used to accelerate the particles and restore energy loss.

Table 5
Characteristics of recently built and planned European synchrotron light sources

Name and location	Energy	Number of cells	Circumference	Emittance
ANKA (Karlsruhe, Germany)	2,5 GeV	8	110,4 m	80 nmrad
SLS (Villengen, Zuric, Switzerland)	2,4 GeV	12	288,0 m	5 nmrad
DIAMOND (Chilton, United Kingdom)	3,0 GeV	24	561,6 m	2,7 nmrad
SOLEIL (Saint-Aubain, France)	2,5 GeV	24	354,0 m	3 nmrad
LLS (Cerdanyola del Vallès, Catalonia)	2,5 GeV	12	251,8 m	8,5 nmrad

The main characteristics of the El Vallès synchrotron light source are given in table 6.

The present design of the ring has a dodecagonal shape and certain minimal final touches are being made to optimise it. Each of the twelve cells will have an array of three bending magnets (the structure known as triple bent achromat [TBA]) that act as light sources. Altogether, it will have twelve straight sections (around 7 metres long), one of which will be used to inject the beams and another will contain accelerator cavities, with the ten remaining sections being available to install insertion devices. The three bending magnets in each cell of the ring generate a dipole magnetic field that bends the high-energy electrons, as well as a quadrupole component that, together with a series of other quadrupole and sextupole magnets, optimises the optics of the ring as an aid to improving the quality of the light produced. Currents of at least 200mA circulate around the ring. It is thereby calculated that the ring will need to be reinjected once a day unless it is decided to be refilled periodically, a possibility which is under study. This ring will be capable of supplying usable light with a critical energy of the order of 5 keV.

While the ring will be able to accommodate up to thirty independent beamlines, the approved project only envisages the funding of five at the present time. Throughout the estimated lifespan of the facility and according to the particular needs of the scientific community in Catalonia, Spain and other countries, the full utility of the ring's capabilities will be increasingly used, as has occurred in similar facilities in other countries.

Table 6
Key parameters of the El Vallès synchrotron light source

Cell type	TBA	units
Electron beam energy	2,5	[GeV]
Number of cells	12	-
Cell length	20.987	[m]
Circumference	251.844	[m]
Electron beam current	250	[mA]
Length of straight sections	8,1	[m]
Natural emittance	8,48	[nm]
Emittance coupling	5%	-
Horizontal emittance	8,08	[nm]
Vertical emittance	0,4	[nm]
Energy dispersion	$8{,}61 \cdot 10^{-4}$	-
Energy loss per orbit	0,42	[MeV]
Critical energy	4,20	[keV]

The anticipated initial technical characteristics of the light emitted by the bending magnets and insertion devices are given in table 7.

Table 7
Anticipated characteristics of the light emitted by the El Vallès synchrotron light source

Emittance device	Shape	Angular spread	Energy	Brilliance
Dipole magnets	Elliptical (0.8 and 0.14 mm axes)	1st axis: 0.6 mrad 2nd axis: 0.4 mrad	0.05 – 2 keV (UV and soft X-rays)	Between 10^{14} and 10^{15} photons per second, per mm^2 and per mrad^2, in a bandwidth between 0.999 λ and 1.001 λ according to selected wavelength λ
Undulators	Elliptical (1.8 and 0.24 mm axes)	1st axis: 0,1 mrad 2nd axis: 0,4 mrad	0,1 – 4 keV (soft X-rays)	Between 10^{18} and 1019 photons per second, per mm^2 and per mrad^2, in a bandwidth between 0.999 λ and 1.001 λ according to selected wavelength λ
Wigglers	Elliptical (1.8 and 0.2 mm axes)	1st axis: 0,4 mrad 2nd axis: 7 mrad	2 – 26 keV (soft and hard X-rays)	Approx. 10^{16} photons per second, per mm^2 and per mrad^2, in a bandwidth between 0.999 λ and 1.001 λ according to selected wavelength λ

Table 8 shows the proposed characteristics for the first five planned beamlines [21].

The light source has been designed so that it has the necessary potential to incorporate developments that occur in forthcoming years. In particular, it will be possible to increase the energy of the light source to 3 GeV and it is also envisaged that certain superconductor bending magnets capable of providing high intensities at relatively high energies will be incorporated. The inclusion of superconductor wigglers may also improve its future performance qualities, enabling the entire volume of users to be catered for and providing optimised, very high intensity beams that are complementary to the ERSF in Grenoble. For more on the technical and scientific details of the project, refer to http://www.lls.ifae.es

The technology transfer deriving from this type of project already began to occur during the process of building the prototypes, which have enabled the viability of the project to be verified, as well as testing the capacity of Spanish enterprises to take on the construction of the fundamental parts of the facility (as mentioned above). The most important of these have been the development of the dipole magnet prototypes, a high stability power source, a magnetic measurements bank and the design for a section of the vacuum chamber. In these cases, Spanish enterprises have developed products that have enabled them to acquire knowledge that has opened up new markets for them. One company built the prototypes for a dipole magnet with a quadrupole component and a field intensity of 1.2 Tesla, which weighs around seven tons and has a precision of 1 in 10,000. It was designed by the group in charge of the project with funding from CDTI. As a result of the experience acquired from this, the company has been able to successfully participate in invitations to tender from other laboratories abroad. A similar thing has happened to the company that made the necessary 1,500 amperes power supply for the electromagnet with a precision of 100 ppm, which is the most precise power source ever built in Spain. Another precision instrument company built a magnetic measurements bank to calibrate the magnet, the quality of which has led to the El Vallès Synchrotron Light Facility being contracted to calibrate and monitor the quality of the entire series of

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[21] According to a study in 1997, although the decision on the actual beamlines to be built will be made later on in accordance with the needs of the majority of users, which may change, and the technological advances that have taken place.

Table 8
Anticipated details and use of the initial five planned synchrotron light beamlines

Line	Energy	Resolution	Other characteristics	Uses
1	0,05-0,63 keV	$<2,5\cdot 10^{-4}$ over the entire range	Transmission of second order harmonics < 10% in the entire spectrum	Absorption, reflection and photoemmision spectroscopies of solids, gases, surfaces and interfaces
2	0,2-1,6 keV	$<4\cdot 10^{-4}$ over the entire range		X-ray spectroscopies, used in many experiments in surface sciences
3	7-26 keV	$2\cdot 10^{-4}$ over the entire range	Transmission of second order harmonics < 1% Luminous flux on the sample of 10^{13} photons per second and per bandwidth of 0.1%	X-ray spectroscopies, protein crystallography, anomalous diffraction or pole diffraction
4	4-12 keV	$5\cdot 10^{-4}$ over the entire range		Spectroscopies: absorbtion reflection, fluorescence, luminescence, EXAFS, pole diffraction and macromolecule crystallography
5	8,4-13,8 keV	10^{-2} over the entire range	Transmission of second order harmonics < 1% Luminous flux on the sample of $5\cdot 10^{13}$ photons per second and per bandwidth of 0.1% Very high collimation (2,3 mrad x 0,3 mrad) Very small beam size at the focal point (2 mm x 0,2 mm)	Diffraction of non-crystalline samples and crystalline samples with very large unit cells that require a wavelength of 1 Å and a luminous flux as high as possible

magnets, each weighing seven tons, built by a British firm for the ANKA synchrotron light facility that has just been put in operation in Karlsruhe. The same process has occurred with the more complex (both dipole and quadrupole) 7.5-ton magnets being built for a synchrotron light source in Canada.

Although the main partners in the new synchrotron light source are the Spanish and Catalan governments, the project has been designed so that it can serve the entire south-west of Europe, especially the south of France, Portugal and later on the countries of the Maghrib. Users in South America should not be ruled out either, given that there is only one low energy synchrotron light facility in Campinas, Brazil.

It is clear that a project of this scale can only come to fruition on the basis of a good proposal plan and a detailed analysis of its viability and usefulness. In this particular case, in somewhat more time than was possibly desirable, a good proposal plan has been made, the usefulness of which has been extensively debated. Despite the fact that it involves a considerable investment by both the Spanish and Catalan governments over the coming years, the benefit and usefulness of building a synchrotron light facility with its enormous and extensive cross-disciplinary scientific nature, together with the innumerable applications in numerous fields is endorsed by similar actions in other countries. Unlike many other scientific projects, justification for the building of such a facility lies in the combined needs of many of its potential users, some of which have opposing objectives. Within the context of increasing R+D endeavours, the go-ahead for this project will undoubtedly contribute to an important step forward in the development of the scientific community in Catalonia and Spain.