ALBA

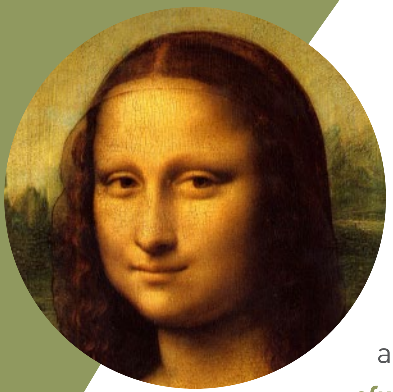
THE POWER OF SYNCHROTRON LIGHT

WHAT IS IT? HOW DOES IT WORK?
WHAT IS THE ALBA SYNCHROTRON'S PURPOSE?

EDUCATIONAL DOSSIER FOR ESO AND BATXILLERAT

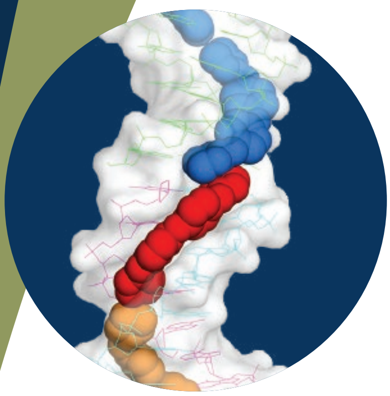
TEACHING DOSSIER

ALBA



La Gioconda or *Mona Lisa* by **Leonardo da Vinci** is one of history's most famous paintings. Her **enigmatic smile**, smooth transitions between highlights and shadows and the blending of her contours are a few reasons for her fame. Leonardo achieved such effects using a **technique known as *sfumato***, which consisted of superimposing paint layers. His talent enabled him to superimpose layers just a few thousandths of a millimetre thick!

Nowadays, we can store games, hundreds of videos and thousands of photos in our pocket. The study of new materials is fundamental to keep increasing our devices' speeds and memory sizes. **Magnetic *skyrmions***, for example, are **nanoscopic structures** that can be used to increase the capacity of current devices.



Malaria is a disease that causes nearly **half a million deaths every year**. The parasites that trigger it have developed resistance to medication, so treatments are no longer as effective. Therefore it is essential to **find new drugs** that act more successfully against the resistant parasites. This is the case of **CD27**, a non-patented compound that may be manufactured in any pharmaceutical laboratory in the world.

WHAT DO THESE 3 STORIES HAVE IN COMMON?

WHAT IS THE ALBA SYNCHROTRON?

A synchrotron is a machine that forces **microscopic particles such as electrons to move at speeds close to the speed of light** around a circumference.

When they perform this movement, the electrons project a very particular type of light: **synchrotron light**. Using this light, **matter can be studied at an atomic or molecular scale**.
So **thanks to synchrotron light, experiments can be conducted** to prove the efficacy of an anti-malarial drug, study objects such as *skyrmions* to increase the memory of electronic devices, or discover exactly how thin the paint layers were that Leonardo da Vinci applied when painting the *Mona Lisa*.

There are about **fifty synchrotrons worldwide**, around twenty of them in Europe. Situated in Cerdanyola del Vallès, **ALBA** is the only synchrotron in Spain.

ALBA Synchrotron.

FILL IN

The ALBA Synchrotron accelerates electrons so that they project light that is used to perform experiments and study matter at a very small scale.

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IS THERE ANY DIFFERENCE BETWEEN THE ALBA SYNCHROTRON AND THE LHC?

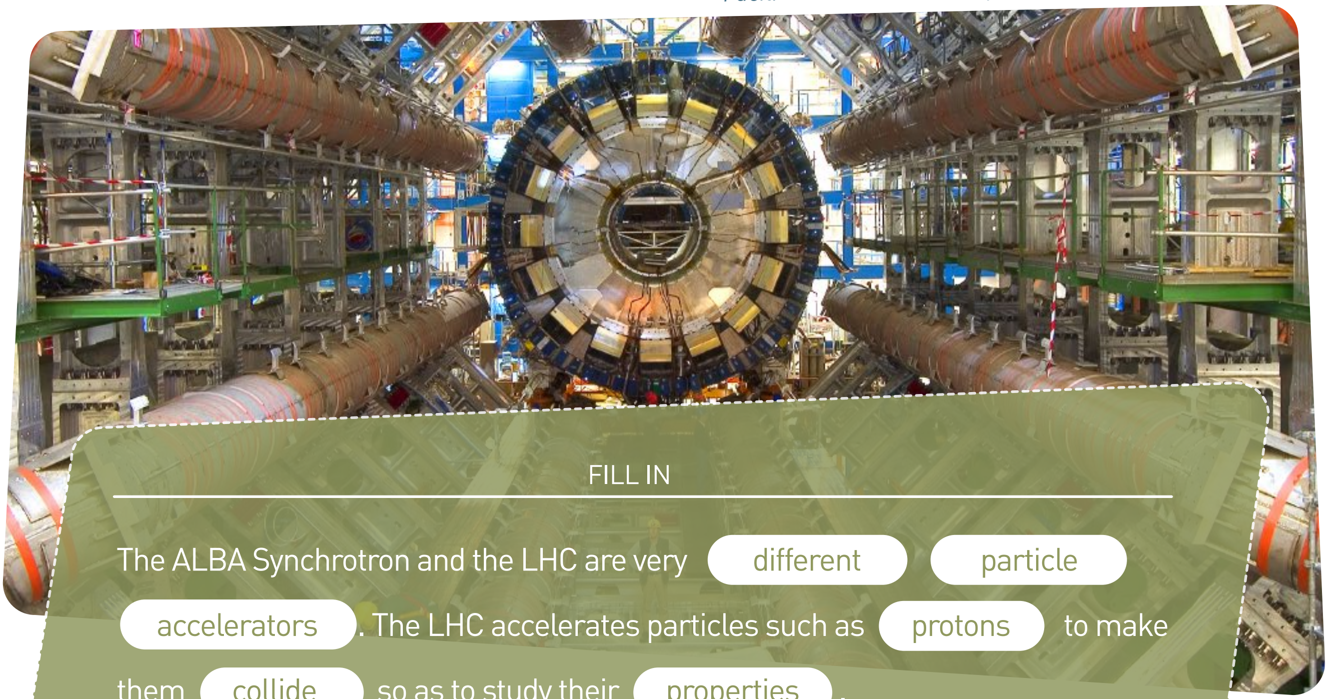
The **Large Hadron Collider (LHC) is the largest and most powerful particle accelerator in the world**. Situated in Geneva, it discovered the famous **Higgs boson** a few years ago. Even though both the ALBA and the LHC are particle accelerators, there are many differences between them:

The **ALBA Synchrotron accelerates electrons**, while the **LHC accelerates particles such as protons**. Since protons are almost 2,000 times heavier than electrons, it takes more to accelerate them and different technology is required.

The objective of the **ALBA Synchrotron is to accelerate electrons to produce light**. This light is used to conduct experiments: for example, cells affected by a virus can be studied so as to find drugs to heal them. In contrast, the **LHC's goal is to accelerate particles like protons, making them strike one another, and study their properties**; or, for example, discover whether they are made of smaller particles.

Because it takes so much energy to accelerate protons, the **LHC is a huge installation**: the tube through which the particles circulate has a **circumference of 28 kilometres**. In contrast, the ALBA Synchrotron's tube has a **perimeter of 268 metres**.

Facilities for the ATLAS experiment at the LHC / CERN.



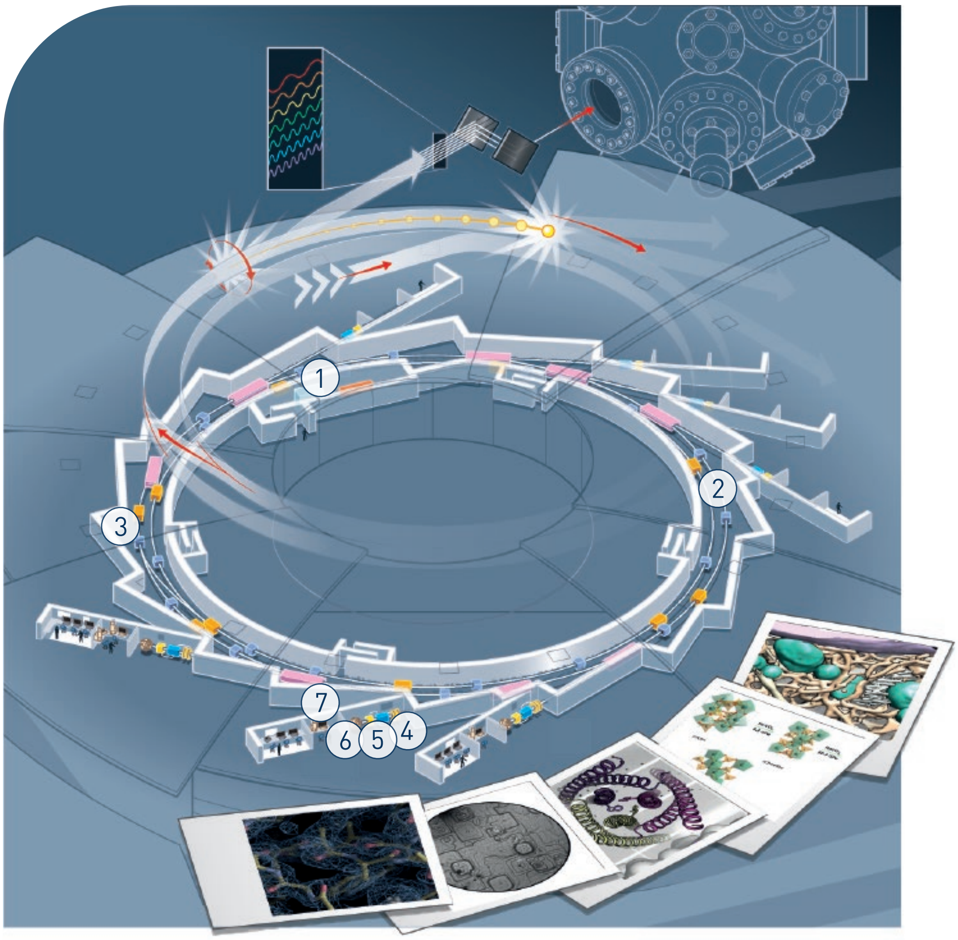
FILL IN

The ALBA Synchrotron and the LHC are very different particle accelerators. The LHC accelerates particles such as protons to make them collide so as to study their properties.

HOW DOES THE ALBA SYNCHROTRON WORK?

Number the following processes according to the order in which they occur and **place them in the correct place** on the diagram:

1. Electrons are extracted from a metal.
2. The electrons are accelerated to speeds close to the speed of light.
3. The electrons are injected into the storage ring so they follow a circular route.
4. The light emitted by electrons is captured and modified according to the experiment run.
5. Once modified, the light is used to illuminate the sample that is to be studied.
6. A detector captures the light after it passes through the sample.
7. The light is stored and analysed to obtain information on the sample.



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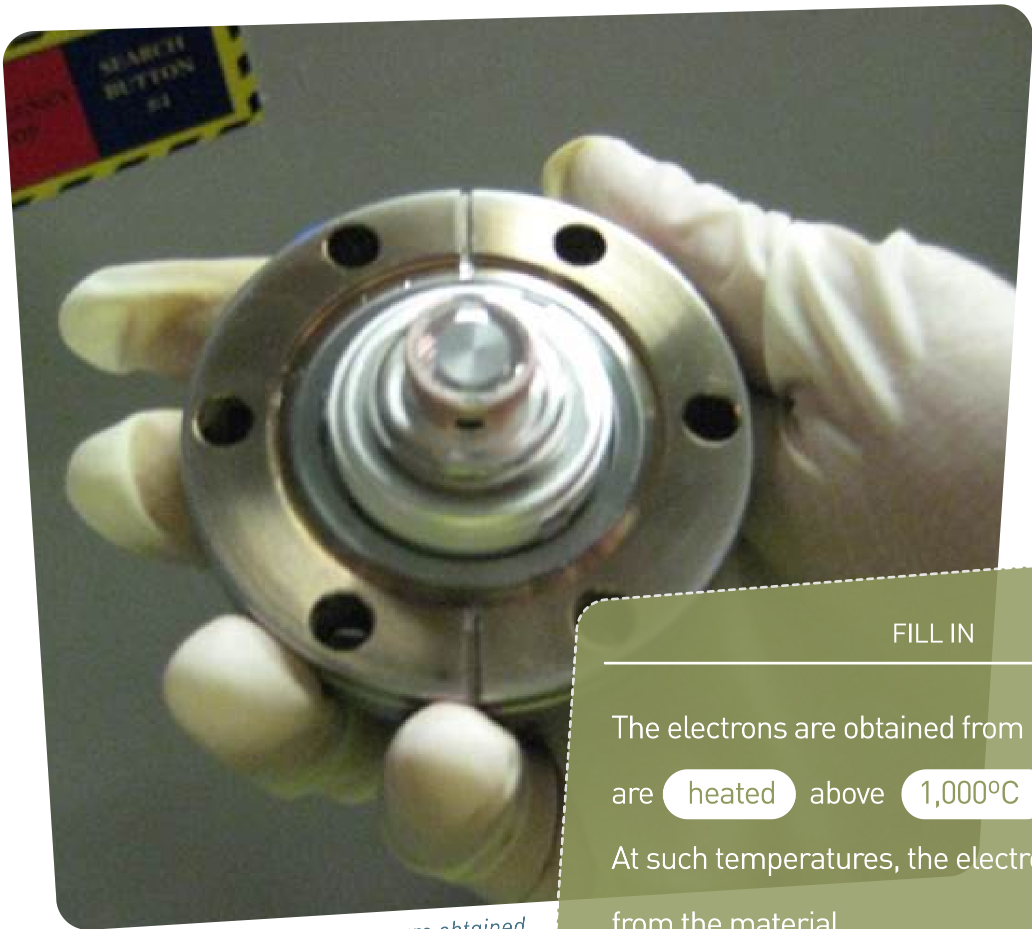
WHERE DO THE ELECTRONS COME FROM?

When we touch an object with our hand and notice it is hot, we are noting that the particles that form it **move and vibrate more quickly than in a cold object**. Temperature is a measure of the movement of particles that make up a body: **higher temperature, more movement**. If the particles in the object we have touched move and vibrate very fast, the impact against our skin can cause pain or even injury. This is what happens with a burn.

If a metal is heated enough, it reaches a point where the electrons inside it move so fast they can jump out of the metal and abandon it. The **ALBA Synchrotron uses this process to obtain electrons**: a metal is heated above 1,000 degrees Celsius until the electrons have enough energy to leave it.



Metal from which the electrons are obtained.

FILL IN

The electrons are obtained from metals that are heated above 1,000ºC.

At such temperatures, the electrons separate from the material.

HOW ARE THE ELECTRONS ACCELERATED?

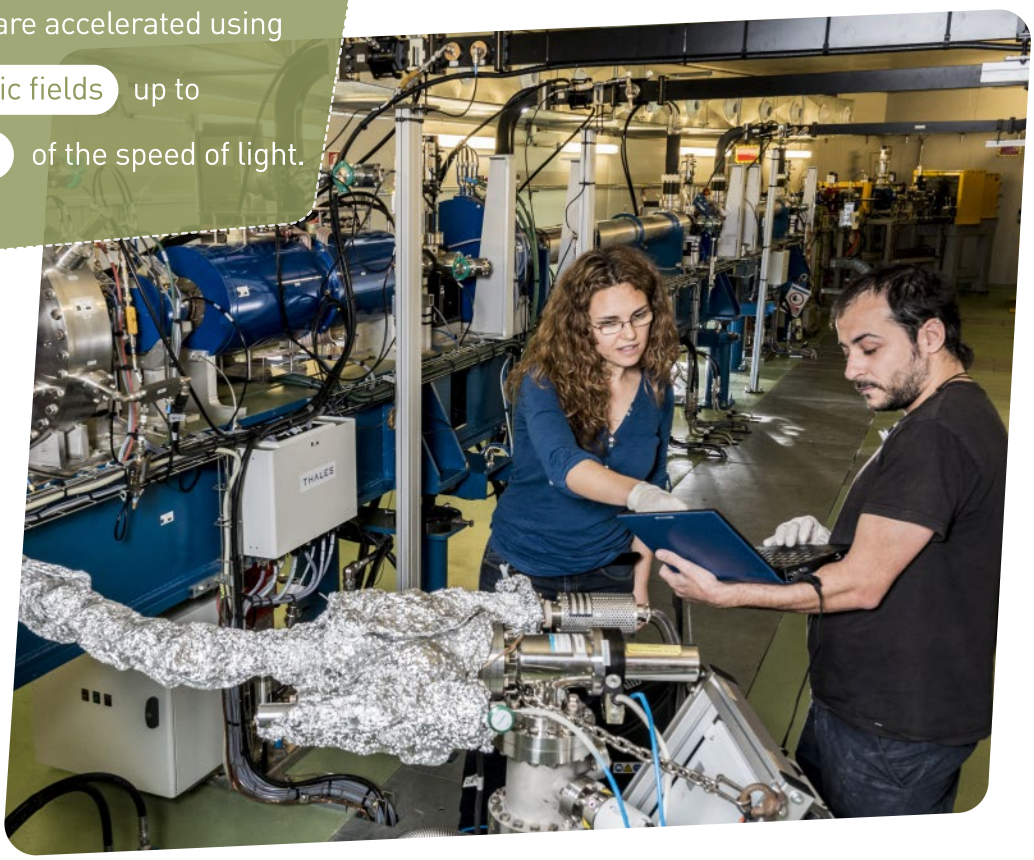
Once they have abandoned the metal, the **electrons accelerate to speeds close to light speed**. This occurs in **two stages**:

In the first, **electrical fields are used to increase the speed of the electrons** along a straight section. In this linear accelerator, the electrons achieve speeds that surpass **99% of the speed of light**.

In the second, the **electrons enter a ring called a *circular accelerator***. Thanks to the use of electromagnetic fields, the electrons follow the circular route defined by the ring and their **speed increases up to 99.9999985% of light speed**.

FILL IN

The electrons are accelerated using electromagnetic fields up to 99.9999985 % of the speed of light.



Linear electron accelerator.

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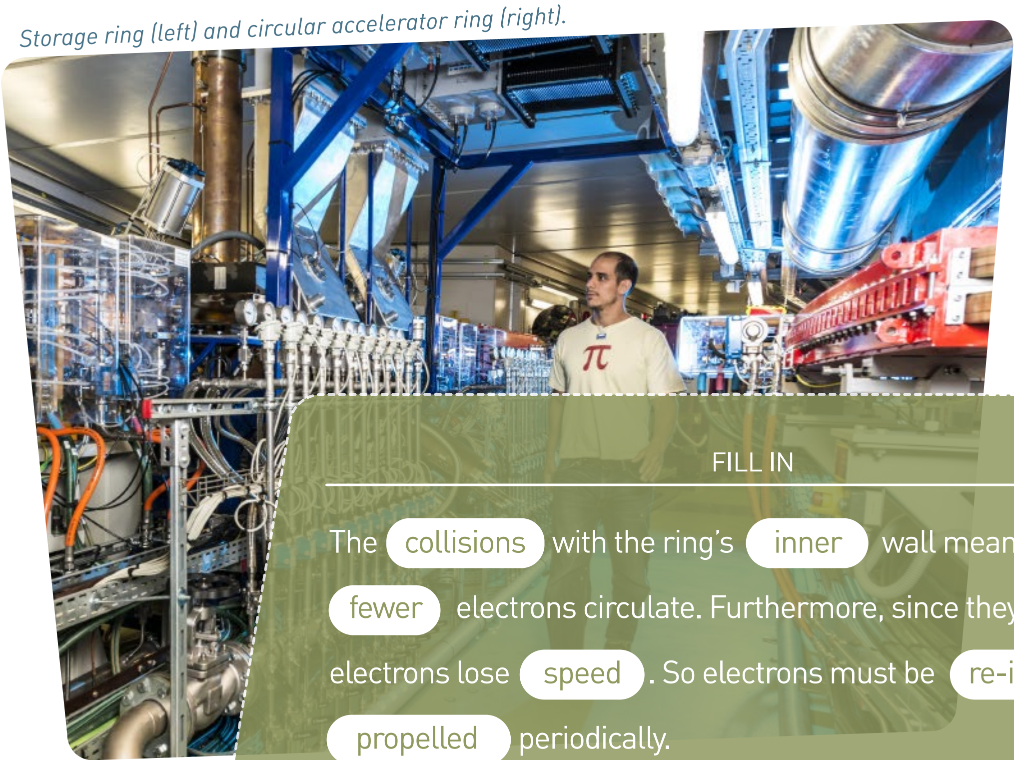
HOW ARE THE ELECTRONS KEPT AT SUCH HIGH SPEEDS?

Once the electrons reach the correct speed, **they are sent to the storage ring**.
There, they follow a **circular route** that has the thickness of a hair and perform a million revolutions per second. While they circulate, **they emit light that is collected and used to conduct experiments**.

As time passes, however, the electrons start hitting the ring's inner walls and continually circulate less. Every 24 hours, the number of electrons is reduced by half. This means that electrons must be continually produced, accelerated and injected into the storage ring.
The ALBA Synchrotron makes an injection like this every 20 minutes.

Furthermore, because they emit light, the **electrons lose energy and circulate more slowly all the time**. To maintain their speed and ensure that the emitted light always has suitable properties for conducting experiments, the electrons must be continually propelled. This is achieved **using electrical fields created in what we call *radiofrequency cavities***.
These cavities must propel the electrons at the same pace as they circulate. **Synchronisation between the propulsion and the speed of the circulating electrons is what gives the name synchrotron to this type of accelerator**.

Storage ring (left) and circular accelerator ring (right).



FILL IN

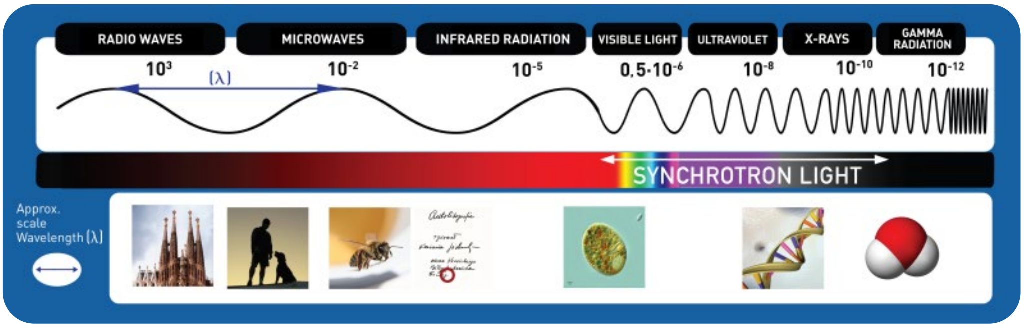
The collisions with the ring's inner wall mean that continually fewer electrons circulate. Furthermore, since they emit light, the electrons lose speed. So electrons must be re-injected and propelled periodically.

WHAT SORT OF LIGHT DO THE ELECTRONS EMIT?

On their circular route, the **electrons emit light of many types**. This includes visible light (blue, red, etc.), but there is also light that the **human eye cannot see**, such as **infrared**, **ultraviolet** and **x-rays**.

The wavelength is one property of waves that gives us an idea of their size. When a wave hits an obstacle of a similar size, it interacts with the object and undergoes alterations. By comparing the wave before and after the interaction, we can gain information on what the object is like. **X-rays have a wavelength of around 10^{-10} metres**; in other words, 0.0000000001 metres. The distance between the atoms that constitute matter is similar. For this reason, **most experiments use x-rays**.

If, instead of using x-rays, we used infrared light, which has a wavelength of 10^{-6} metres – or rather, one thousandth of a millimetre – we would see no difference in the light before and after the interaction. The wavelength is far larger than the atoms, so they are not capable of altering it. The situation is the same as if a series of waves in the sea collided with a floating cork or with a vessel 20 metres long. In which case would the waves be most affected?



The different wavelengths of light.

FILL IN

In a synchrotron, infrared, visible, ultraviolet light and x-rays are produced. Since it has a wavelength similar to the distance between atoms, the light that is most used in experiments is x-ray light.

HOW IS THE LIGHT EMITTED FROM ELECTRONS USED?

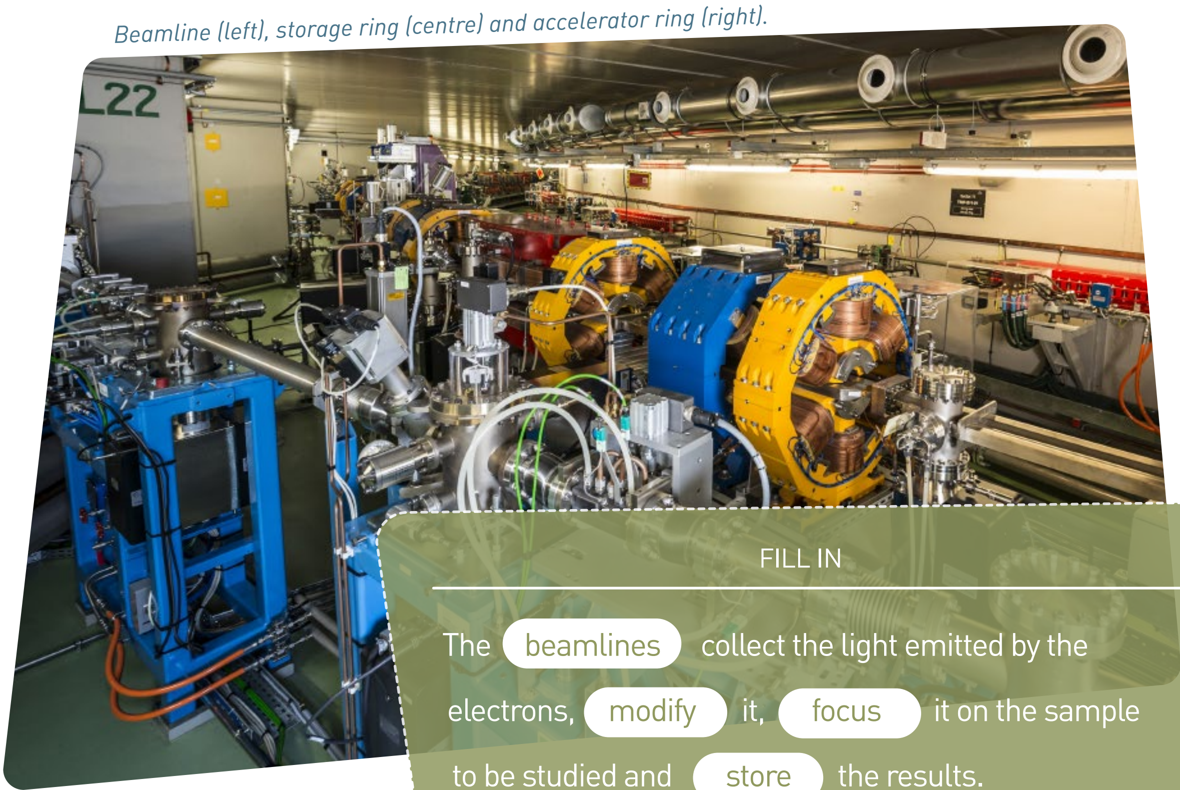
When they circulate, the **electrons emit light in the direction of their movement**. This means that just at the moment it is emitted, the **light moves in the same direction and manner as the electrons**. But the electrons **move in a circle** as a result of the electromagnetic fields. **The light, in contrast, continues moving in a straight line** and so on a **tangent to the electrons' circular route**.

The **light emitted** by the electrons is collected and used in what are **called *beamlines***. These devices are placed to follow the trajectory of the light: **straight and tangential to the ring**.
Along these beamlines are apparatus that modify the light according to the experiment conducted.

Once modified, other apparatus focus it onto the sample to be studied. After hitting the sample, a **detector captures the resulting light and stores the data so it can be analysed**.

The ALBA Synchrotron has 8 beamlines while 3 more are being built.

Beamline (left), storage ring (centre) and accelerator ring (right).



FILL IN

The beamlines collect the light emitted by the electrons, modify it, focus it on the sample to be studied and store the results.

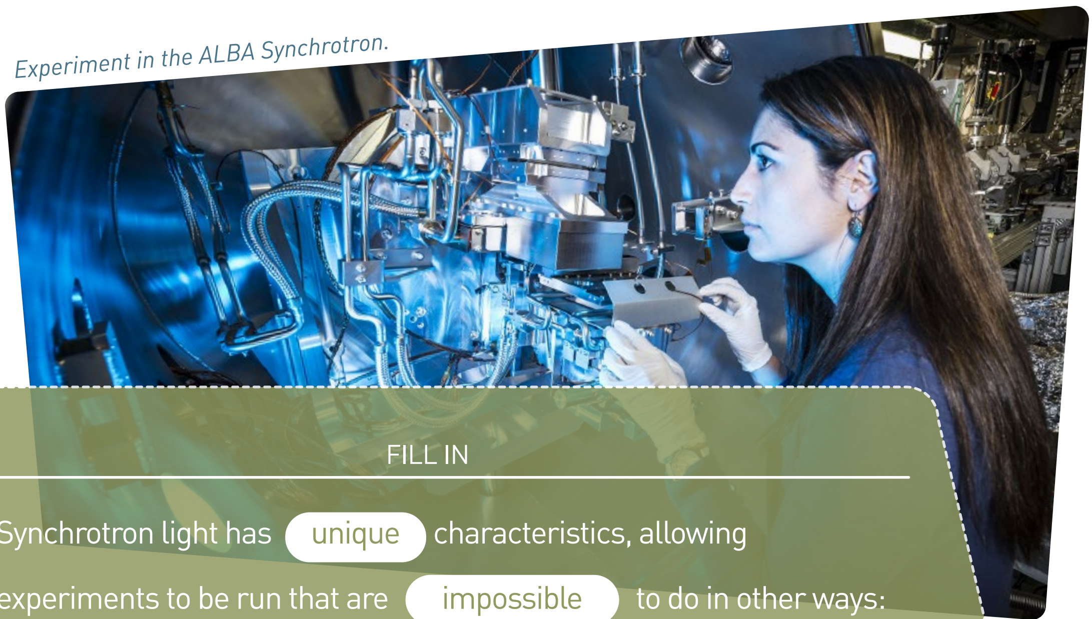
WHAT ADVANTAGES DOES SYNCHROTRON LIGHT HAVE?

As well as synchrotrons, there are many **other devices that produce x-rays**. The machines that take x-rays in hospitals are one example. Why are these other machines, which are simple and cheap, not used to conduct the same experiments? The fact is the **x-rays produced in a synchrotron possess unique properties** that enable experiments to be conducted that cannot be carried out any other way:

A **synchrotron can produce many types of x-ray**, while other machines can only produce one specific type. Therefore, a **synchrotron can be used to conduct many more experiments**. The x-rays produced in a synchrotron are very bright. As happens when we illuminate a room using a powerful torch, when we illuminate a sample using very bright x-rays, we can see details we would not see if the light was weaker.

Synchrotron light is polarised light. That means it vibrates in a very specific direction. There are materials that respond very differently to light depending on how it vibrates. So **polarised light enables us to run experiments that cannot be conducted using unpolarised light**. A synchrotron can produce pulsed light; in other words, it can make the light intermittent. Furthermore, this intermittence can be very fast, **up to 1,000 flashes a second**. This lets you do something very similar to taking photos one right after the other of the sample, so that **very fast processes like chemical reactions can be studied**.

Experiment in the ALBA Synchrotron.



FILL IN

Synchrotron light has unique characteristics, allowing experiments to be run that are impossible to do in other ways: including many types of x-rays, it is bright, polarised and pulsed.

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WHAT TECHNIQUES DO THEY USE IN THE ALBA SYNCHROTRON?

10.1

X-RAY DIFRACCTION

When the sample is illuminated, different things can happen. Sometimes the atoms divert the x-rays. If the x-rays are captured on-screen after passing through the sample and the deviations they underwent are studied, scientists can deduce what the atoms causing the deviations were like and how they were arranged. **This technique is called *x-ray diffraction***. Depending on **how the atoms of the sample are arranged** in space, **three types of diffraction exist**:

If the atoms are ordered and form structures that regularly repeat in space, then the way they deviate the x-rays from their path can be accurately observed. This lets us exactly deduce the internal structure of the sample in 3D. **This type of diffraction is called *single crystal***.

If the atoms are not so well ordered, you generally see an image on-screen in the shape of rings. From these rings, thanks to mathematical techniques, you can obtain the internal structure of the sample in 3D. **This process is called *powder diffraction***.

Lastly, **if the sample is formed of structures on a larger scale** such as plastics, fibres or live tissue, the resulting image offers information on the internal structure of the sample and the changes it has undergone due to environmental conditions or physiological processes. **This is called *non-crystal diffraction***.

FILL IN

X-ray diffraction consists of illuminating the sample using x-rays and analysing the deviations the rays have undergone to deduce what the sample is like internally.

ALBA

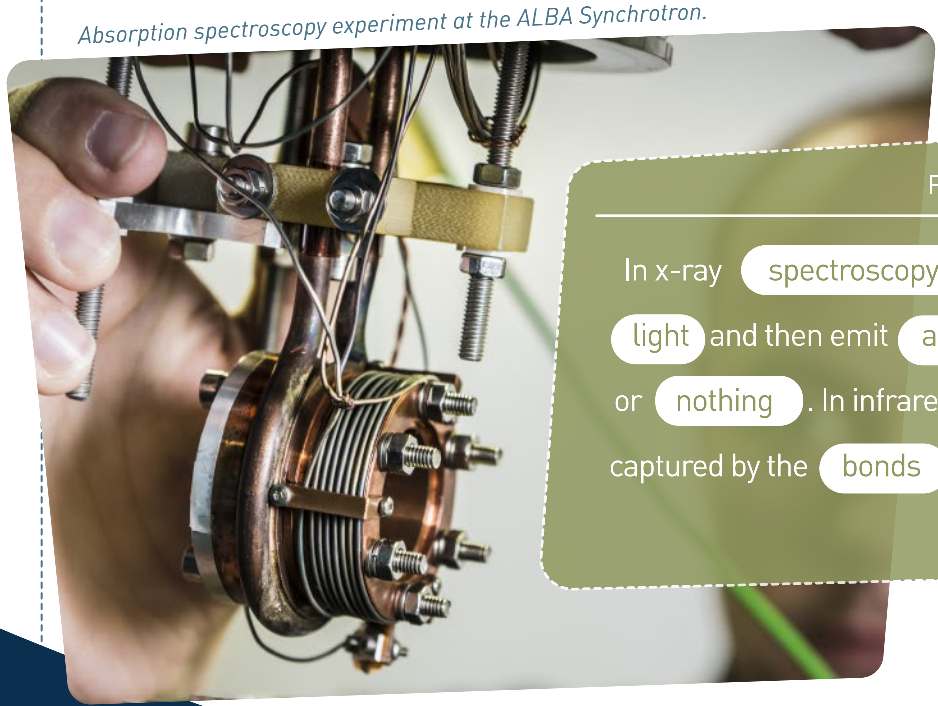
10.2 WHAT TECHNIQUES DO THEY USE IN THE ALBA SYNCHROTRON?

X-RAY SPECTROSCOPY

When a sample is illuminated, sometimes the material absorbs part of the x-rays and after a while, as a result of that absorption, it emits another type of light. This light's properties depend on the material's internal structure. So analysing it lets us obtain information on what the sample is like. **This process is called *spectroscopy*. The absorption of x-rays and later emission of light can happen in several ways.**

- In the process called ***photoemission***, the sample emits electrons, which can be captured to obtain information on its insides.
- If the material accumulates light in its structure and the amount accumulated is analysed, the process receives the name ***absorption***.
- It can also happen that the atoms in the sample absorb light and emit only one part, in a process known as ***dispersion*** or ***fluorescence***.
- Lastly, the possibility exists that it is not the atoms that absorb the light but the bonds that join them. Because every bond can absorb one specific type and quantity of energy, analysing this type of absorption allows us to know how the atoms inside the sample are joined. This process is called ***infrared spectroscopy***.

Absorption spectroscopy experiment at the ALBA Synchrotron.



FILL IN

In x-ray spectroscopy, the sample can capture light and then emit another type of light, electrons or nothing. In infrared spectroscopy, the light is captured by the bonds within the sample.

10.3 WHAT TECHNIQUES DO THEY USE IN THE ALBA SYNCHROTRON?

X-RAY MICROSCOPY

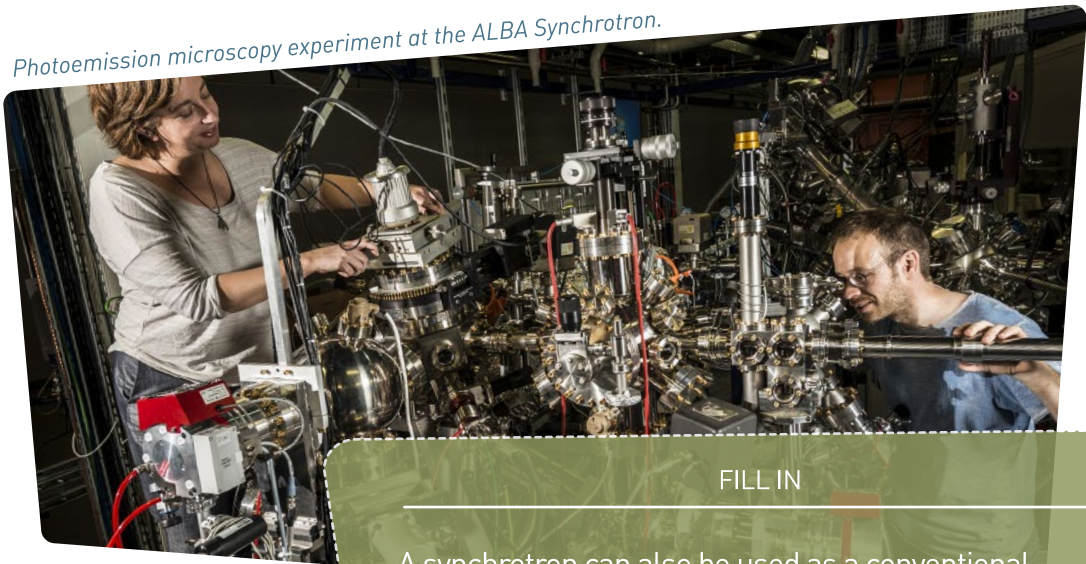
Synchrotron light can also be used to observe samples as one does with a conventional microscope. The advantage is that **thanks to the x-rays, very small objects can be observed**, which cannot be distinguished using a visible-light microscope. This observation can occur in several ways.

When the x-rays excite the electrons on the surface layer of the sample, lenses can be used to reconstruct the surface of the sample from these electrons. **This process is called *photoemission electron microscopy***.

If the sample is irradiated with low-energy x-rays, images can be taken from different angles using the microscope. This allows the sample's 3D structure to be reconstructed. **This technique is called *x-ray transmission microscopy.***

A synchrotron can also combine infrared spectroscopy and optical microscopy. This allows biological systems to be analysed using **infrared light in what is called *infrared microscopy***.

Photoemission microscopy experiment at the ALBA Synchrotron.



FILL IN

A synchrotron can also be used as a conventional microscope. Thanks to the properties of the x-rays this technique enables scientists to observe smaller objects than visible-light microscopes.

WHAT CAN BE RESEARCHED AT THE ALBA SYNCHROTRON?

The **x-rays produced at the ALBA Synchrotron** can be used to **analyse samples from highly diverse materials and fields**.

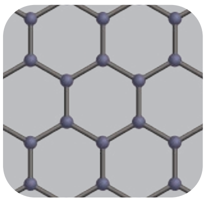
BIOMEDICINE

Development of new treatments and early diagnosis techniques for **skin cancer**, the most frequent type of cancer.
▶ https://youtu.be/ml4M7t5456E

Study of liver cells affected by **hepatitis C,** with the goal of designing improved treatments.
▶ https://youtu.be/d-aDMTemxu0

MATERIALS SCIENCE

Study of new magnetic materials to enlarge the **memory** of computers and mobile phones.



Study of new materials such as **graphene**, a harder material than diamonds, and stronger than steel.

FOOD & BEVERAGE SECTOR

Study of the **crystallising** process of chocolate to achieve new and pleasanter textures.

Study of **wheat enriched with selenium**, a primary nutrient, to determine the best growing and enrichment techniques.
▶ https://youtu.be/j-ohGQP75oE

ENVIRONMENT

Analysis of **soil contaminated with arsenic** with the goal of eliminating this waste.

Study of **catalysts** that can improve the efficiency of electrical vehicles.
▶ https://youtu.be/orO0GxYflwA

CULTURAL HERITAGE

Study and **removal of stains** on the paintings in Saint Michael's Chapel in Pedralbes Monastery.
▶ https://youtu.be/CaH4cD_gX2I

Analysis of stained-glass windows in Segovia Cathedral so as to **know how they were made** and improve their state of conservation.

WHO CAN USE THE ALBA SYNCHROTRON?

The **ALBA Synchrotron is an accelerator managed** by a consortium made up of **Spain and the Government of Catalonia** that started operations in **2012**.

The **ALBA Synchrotron is available to researchers in the public sector and private companies**. Proposals for experiments are analysed by a group of international scientists, who select the most relevant. **Public researchers** can use the Synchrotron without paying anything, but they must **undertake to publish the results of their experiments so that everybody knows and benefits from the results. Companies, in contrast, must pay to conduct experiments, but are not obligated to publish the results**.

More than **200 people** work in the **ALBA Synchrotron**.

TEACHING PROPOSAL
Before the visit

1. LET'S SIMULATE A SYNCHROTRON

Material: LED light, small button battery, adhesive tape, transparent balloon.

Turn on the light by making contact with the battery and fix it with adhesive tape so it stays lit. Put the light inside the balloon and inflate it. Seal the balloon closed with a knot and turn off the light in the room. Turn the LED inside the balloon so that from outside you see a circumference of light.
This experience helps you understand how a synchrotron basically operates: particles revolve and emit light. What would happen if the balloon was opaque and you had holes from which the light could escape? In which direction would it shine?

Inside a synchrotron, electrons travel a circular route because highly powerful magnets force them on that path. Light, in contrast, travels in a straight line. So the light moves along a tangent from the circumference. In a synchrotron, this light, like the light that would spill from the holes in an opaque balloon, is collected at diverse points on the circular route and used in experiments.

2. LET'S DIFFRACT LIGHT

Material: A laser pointer, black adhesive tape, scissors and a white screen or wall.

Turn off the lights and turn on the laser pointer. Focus the pointer onto the wall and observe the shape of the spot of light. It should be a circle. Next, cover the hole on the pointer which emits light with three very thin strips of adhesive tape. Two very slim parallel cracks should remain through which light can pass. Focus the pointer on the wall again and observe the shape of the light. You should not see two strips of light, but a pattern in which several strips of light and darkness alternate, which get weaker the farther they are from the centre of the image.

This phenomenon is due to the undulating properties of light. When they pass through the cracks, the light waves become two points of light that interfere with each other. In places, this adds to the light's intensity while in others, it counteracts it. At minute 4:14' of this video you can find the same experience conducted in a more tangible medium: the water's surface. You can clearly see how at some points the waves travelling over the water's surface come together to increase the wave's size, and in others, they cancel it out, so the wave disappears.

▸ https://www.youtube.com/watch?v=Iuv6hY6zsd0

(This video includes subtitles in Spanish, activated using the Settings button on the video itself).

TEACHING PROPOSAL
After the visit

1. LET'S MEASURE THE WIDTH OF A HAIR

Material: A laser pointer, a ruler, adhesive tape, a white screen or wall, several hairs (as different as possible).

Attach the hair to the pointer using adhesive tape, so that it is positioned over the light beam. Place it on a table (or a stable surface to avoid movement) at a distance of one to three metres from the white screen or wall (the optimum distance may depend on the type of laser used). On the wall you should see a number of strips of light, symmetrical in relation to a central strip of light. Measure the distance between the centres of the two strips of light situated directly on each side of the central light strip. Apply the following equation:

$$\text{Thickness of hair} = \frac{\text{Laser wavelength} \cdot \text{Distance between the hair and the wall}}{0.5 \cdot \text{Distance between the light strips}}$$

Remember that the wavelength is generally given on the laser packet.
Measure the thickness of several hairs and calculate the average. You should obtain a value close to a tenth of a millimetre.

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