# Synchrotron light

Synchrotron light is used today to carry out fundamental research in areas as diverse as condensed matter physics, pharmaceutical research and cultural heritage.

COURTESY OF DIAMOND LIGHT SOURCE

## What is synchrotron light?

Synchrotron light (also known as synchrotron radiation) is electromagnetic radiation that is emitted when charged particles moving at close to the speed of light are forced to change direction by a magnetic field. Synchrotron light can be produced naturally by astronomical objects, such as the Crab Nebula – a supernova remnant in the Taurus constellation. Since the late 1940s synchrotron light has been artificially generated using synchrotrons – particle accelerators that gave the phenomenon its name.

Synchrotron radiation spans a wide frequency range, from infrared up to the highest-energy X-rays. It is characterised by high brightness – many orders of magnitude brighter than conventional sources – and the light is highly polarised, tunable, collimated (consisting of almost parallel rays) and concentrated over a small area. When synchrotrons were first developed, their primary purpose was to accelerate particles for the study of the nucleus, not to generate light. Today on the other hand, while a few are still used as colliders for high-energy physics experiments such as the Large Hadron Collider at CERN, there are more than 50 synchrotron light sources around the world dedicated to generating synchrotron light and exploiting its special qualities. These machines support a huge range of applications, from condensed matter physics to structural biology, environmental science and cultural heritage.

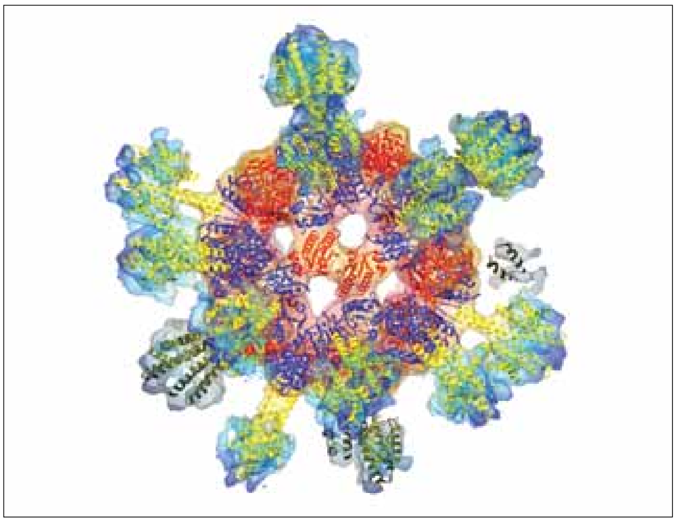
Earlier accelerators, called cyclotrons, had fixed magnetic fields. Because the bending of a charged particle is inversely proportional to its momentum, cyclotrons were limited to fairly low energies otherwise they became unaffordably large. By collecting the particles into bunches and synchronising a rise in magnetic-field strength with the increasing energy of the charged particles, the particles could be accelerated to higher energies while being constrained to a fixed circular path. Thus the synchrotron was born, with the first observation of artificial synchrotron light occurring at General Electric in the US in 1947.

## The science

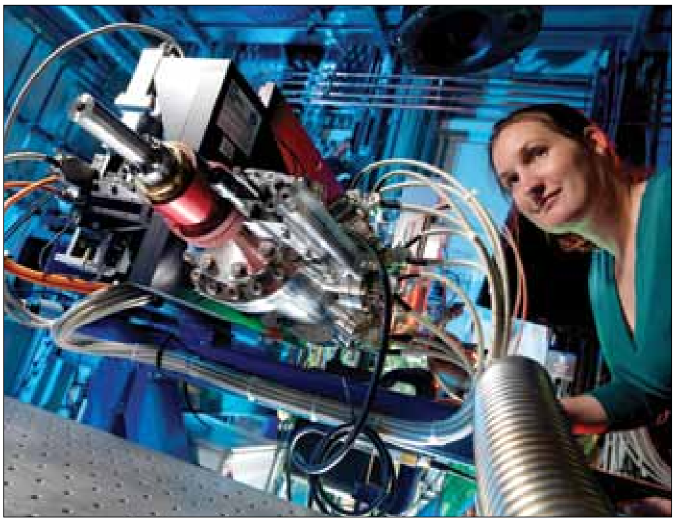
British theoretical physicist James Maxwell's classical theory of electromagnetism (first fully documented in 1873) explains that charged particles moving through a magnetic field generate electromagnetic radiation. By requiring Maxwell's equations to be true in all inertial (non-accelerating) frames of reference, Einstein's theory of special relativity fully explained the complete characteristics of synchrotron light generated by electrons travelling along a circular path at relativistic speeds. The radiation produced in synchrotrons is focused in a narrow cone, perpendicular to its acceleration direction and parallel to the directional motion of the electrons.

Synchrotron light is the brightest artificial source of X-rays, allowing the detailed study of molecular structures, which has led to the award of Nobel prizes in a number of fields (see timeline).

In 1956, two American scientists, Diran Tomboulian and Paul Hartman, were granted use of the 320 MeV synchrotron at Cornell University. In addition to confirming the spectral and



COURTESY OF RICK LEWIS AND JON MARLES-WRIGHT, NEWCASTLE UNIVERSITY



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angular distribution of synchrotron light, they carried out the first X-ray spectroscopy study using synchrotron light. Five years later, the National Bureau of Standards in the US modified its 180 MeV machine to allow synchrotron light to be harvested for experiments. These became known as the first-generation synchrotrons – machines built for smashing nuclei apart using electrons, which were later used for synchrotron-light experiments.

Over the coming decades, as demand grew for the use of first-generation synchrotron machines, pioneering advances led to a number of developments, such as the storage ring, which allowed particles to circulate for long periods of time providing more stable beam conditions, benefiting both particle physicists and synchrotron users. One of the most significant developments took place in the late 1970s when plans were approved to build the world's first dedicated synchrotron light source producing X-rays (Synchrotron Radiation Source – SRS) at Daresbury in the UK, which started user experiments in 1981. The US, Japan and others also built second-generation machines, while other first-generation machines received upgrades to allow for more experiments.

For scientists carrying out spectroscopy experiments, the brightness of the beam reaching the sample determined the resolving power of the results. For crystallographers, especially those looking at small crystals with large unit cells, high brightness was important to resolve closely spaced diffraction spots. As second-generation machines were optimised to produce brighter beams, a fundamental limit was approaching. To meet the increasing demands of a growing synchrotron user community, a new approach was required: insertion devices.

Insertion devices are arrays of magnets placed into the straight sections of the storage ring, which could be retro-fitted to second-generation machines and were quickly incorporated into existing synchrotrons. Insertion devices help to create a beam that is very bright and with intensity peaks with a wavelength that can be varied by adjusting the field strength (often the gap between two magnet arrays).

The increased brightness made data collection faster, and tunable wavelengths benefited crystallographers and spectroscopists alike. By the early 1990s machines were being designed with insertion devices in place from the start, and the first such third-generation source, the European Synchrotron Radiation Facility (ESRF) in Grenoble, France, started operating in 1994. There are now more than 50 dedicated light sources in the world, combining both second- and third-generation machines, which cover a wide spectral range from infrared to hard X-rays.

The experimental configurations of different synchrotron facilities are quite similar. The storage rings where the light is generated have many ports, which each open onto a beamline, where scientists set up their experiments and collect data. The beamlines, however, can vary a lot in the details depending on the experimental methods they are used for. The Diamond Light Source in Oxfordshire became Britain's newest synchrotron light facility in 2007 and in August 2008 it was Britain's only synchrotron source following the closure of the SRS. It represents the largest single UK science investment for 40 years and will have the capacity to host 40 beamlines. The Diamond Light Source supports a huge range of scientific disciplines, including condensed matter physics, chemistry, nanophysics, structural biology, engineering, environmental science and cultural heritage.

## Applications

● *Life science*
Pharmaceutical companies and medical researchers are making increasing use of macromolecular crystallography. Improvements in the speed of data collection and solving structures mean that it is now possible to obtain structural information on a timescale that allows chemists and structural biologists to work together in the development of promising compounds into drug candidates. Both the anti-flu drug Tamiflu and Herceptin – used to treat advanced breast cancer – benefited from synchrotron experiments. Using synchrotron light in the infrared range, pioneering research is underway into developing new cancer therapies that can be tailored to the individual patient. In 2009, the Medical Research Council used the Diamond Light Source to compare the structure of hemagglutinin from the flu-virus strain that caused the 1957 "Asian" pandemic with the 1918 and 1968 outbreaks, to discover why some avian flu viruses are more able than others to jump the species gap.

● *Engineering*
Synchrotron X-ray beams allow detailed analysis and modelling of strain, cracks and corrosion as well as *in situ* study of materials during production processing. This research is vital to the development of high-performance materials and their use in innovative products and structures. The Diamond Light Source has been used to study the processes behind pitting corrosion, which attacks the so-called corrosion-resistant metals used in containers for nuclear waste, and to understand how applied stresses can cause cracks to propagate through materials.

● *Environmental science*
Synchrotron-based techniques have made a major impact

## Timeline

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| **1873** | James Clerk Maxwell publishes his theory of electromagnetism. |
| **1895** | Wilhelm Röntgen discovers X-rays, for which he wins the inaugural Nobel Prize in Physics in 1901. |
| **1897** | Sir Joseph Larmor shows mathematically that radiation is emitted by accelerated charged particles. |
| **1898** | Alfred-Marie Liénard realises particles moving in a circle will produce this radiation as a result of centripetal acceleration. Years later, this work was built on by George Adolphus Schott, the British mathematician, who published his classical work on electromagnetic radiation. |
| **1912** | Max von Laue obtains the first X-ray diffraction pattern of a crystal. |
| **1914** | Sir William Henry Bragg and William Lawrence Bragg in London and Manchester, respectively, extend the use of X-ray diffraction as a technique for determining crystal structure, for which they shared a Nobel Prize in Physics in 1915. |
| **1946** | First synchrotron operates in Woolwich, UK. |
| **1947** | First observation of synchrotron light. |
| **1949** | American physicist Julian Schwinger documents the full theory of a relativistic electron on a circular path producing radiation. |
| **1953** | Structure of DNA solved using X-rays. |
| **1956** | First experiments using synchrotron light take place at Cornell, US. |
| **1959** | Max Perutz at the Cavendish Laboratory in Cambridge uses X-ray crystallography to determine the structure of haemoglobin, for which he wins the Nobel Prize in Chemistry in 1962. |
| **1964** | The DESY synchrotron in Germany begins operation for both high-energy physics and synchrotron-light experiments. |
| **1966** | First experiments in the UK at Glasgow synchrotron. |
| **1977** | First demonstration of free-electron-laser (FEL) principle at Stanford, US. |
| **1981** | The Synchrotron Radiation Source (SRS) starts operating in Daresbury, UK. It is the first dedicated X-ray producing synchrotron source. |
| **1994** | The first third-generation synchrotron source, the ESRF in Grenoble, France, goes into operation. |
| **1997** | Sir John Walker wins the Nobel Prize in Chemistry for his work on the structure of Bovine F1 ATP synthase, based on research using the SRS. |
| **2000** | The SASE principle for an FEL is successfully demonstrated at DESY. |
| **2005** | FLASH, the first FEL in the soft X-ray range, goes into operation at DESY. |
| **2007** | The Diamond Light Source starts operation as a next-generation user facility in the UK. |
| **2008** | The SRS closes after 28 years of operation and 2 million hours of user beamtime. The Diamond Light Source takes over as the UK national facility. |
| **2009** | The Linac Coherent Light Source, the first hard X-ray XFEL, goes into operation in the US. Venkatraman Ramakrishnan, Thomas A Steitz and Ada E Yonath are awarded the Nobel Prize in Chemistry for revealing the structure of the ribosome, for which they used synchrotron light. |

in the field of environmental science in the last 10 years. High brightness allows high-resolution study of ultra-dilute substances, the identification of species and the ability to track pollutants as they move through the environment. Synchrotrons have been used to develop more efficient techniques for hydrogen storage and to study the way in which depleted uranium disperses into the local environment. Tiny heavy-metal samples excreted from earthworms have been compared with contaminated soil samples, revealing how earthworms survive in these environments and introducing the idea that earthworms could help to decontaminate land.

> **“Synchrotron light is the brightest artificial source of X-rays.”**

- *Physics and materials science*

Determining the properties and morphology of buried layers and interfaces is an important area in solid-state science with synchrotrons being the meeting ground of state-of-the-art theory and high-precision experimental results. Many of the technological products of materials science are based on thin-film devices, which consist of a series of such layers. Structural studies of *in situ* processing of semiconducting polymer films are also likely to be an important area of growth in the coming decade. Diffraction of high-intensity X-ray beams is an ideal technique to study spin, charge and orbital ordering in single-crystal samples to understand high-temperature superconductivity. The SRS was used to help study giant magneto-resistance (GMR), which is now used in billions of electronic devices worldwide.

- *Cultural heritage*

Cultural heritage is a rapidly expanding area of research using synchrotrons. Scientists are using non-destructive synchrotron techniques to find answers to big questions in palaeontology, archaeology, art history and forensics. Scientists in the UK have used the SRS and the Diamond Light Source to study samples from the Tudor warship the *Mary Rose* to enhance their conservation techniques, and the ESRF has been used to study insects more than 100 million years old, preserved in amber.

## Impacts

Seven Nobel Prizes in Physics have been awarded for X-ray related work. For example, British physicists Sir William Henry Bragg and William Lawrence Bragg shared the 1915 prize for using X-ray diffraction as a technique to determine crystal structure.

Synchrotron facilities have had a positive and significant impact on many areas. In technology, research into GMR is now benefiting data storage in billions of electronic devices like iPods – a market generating £1 bn per quarter. At the time the SRS closed in 2008, 11 of the top 25 companies in the UK R&D Scoreboard had used the facility.

Sir John Walker was awarded the Nobel Prize in Chemistry in 1997 for his work on the structure of Bovine F1 ATP Synthase – the first synchrotron-based Nobel prize. In 2006, the Nobel Prize in Chemistry was awarded to Prof. Roger Kornberg for his synchrotron-based research into how genes copy themselves, a process involved in many human diseases and stem-cell treatment. The structure of the foot-and-mouth-disease virus was determined first at the SRS, leading to potential new vaccines that could save the UK £80 m if another outbreak were to occur. Synchrotron light is considered essential in modern pharmaceutical research, illustrated by the 14% investment in the Diamond Light Source by the Wellcome Trust, the UK's largest non-governmental funding body for biomedical research.

Throughout the lifetime of synchrotron facilities, 300 local businesses benefited from the SRS, with £300 m being awarded in contracts – the financial impact on the local economy throughout its lifetime is estimated to be almost £1 bn. Similarly, more than 1000 companies have benefited from construction or technology contracts for the Diamond Light Source and a quarter of the science carried out at the ESRF links directly to industry.

## Key facts and figures

- There are around 50 synchrotron light sources around the world.
- Synchrotrons are used by industry, with 11 of the companies in the UK Top 25 R&D Scoreboard 2008 having used the SRS.
- Pharmaceutical companies use synchrotrons as part of the drug-development process, creating new products that have the potential to save the UK economy huge sums of money.
- 19 Nobel prizes have been awarded for research involving X-rays; nine in chemistry (of which four used synchrotron X-rays), seven in physics and three in medicine.
- Synchrotron sources boost local economies through local construction and maintenance contracts worth hundreds of millions of pounds.

## Useful links

- www.lightsources.org/
- www.diamond.ac.uk/Home/About/Synchrotrons.html
- http://xdb.lbl.gov/Section2/Sec_2-2.html
- www.esrf.eu/files/Brochures/LeadingScienceforEurope.pdf
- http://en.wikipedia.org/wiki/Synchrotron_light

## Future developments

The demand for synchrotron light has meant that third-generation machines are being built around the world, and existing machines continue to be developed to provide brighter X-rays, increased user hours and more flexible experimental stations. The modular nature of modern synchrotrons means that new technologies can be incorporated into existing machines as they arrive. By using powerful linear accelerator technology, fourth-generation sources – known as free-electron lasers (FELs) – can generate shorter, femtosecond pulses but with the same intensity in each peak as synchrotron sources emit in one second, producing X-rays that are millions of times brighter in each pulse than the most powerful synchrotrons. FELs won't replace third-generation machines, but will provide facilities that enable studies at higher peak brightness.

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