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An introduction to the Australian Synchrotron

Australian Synchrotron

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What is it?

The Australian Synchrotron is a scientific research facility located in south-east Melbourne, Victoria, at the heart of a technology and innovation hub. The Australian Synchrotron produces powerful beams of light that can be used to examine the atomic and molecular detail of a wide range of materials. The facility, which is the nation's most significant piece of scientific infrastructure, actively supports the research needs of Australia's major universities and research centres, and of businesses ranging from small-to-medium enterprises to multinational companies.

Synchrotron techniques are used in many important areas, including advanced materials, agriculture, biomedics, defence, environmental sustainability, food technology, forensics, oil and gas, mining and nanotechnology.

Using synchrotron light to conduct experiments offers several advantages over conventional techniques. The results are superior in terms of accuracy, quality, robustness and the level of detail that can be seen, and can be collected much faster than with traditional laboratory tools.

Fundamental and applied research conducted across these fields using synchrotron technology benefits both the community and a diverse range of industries.

What is a synchrotron light source?

A synchrotron light source is a machine that accelerates electrons to produce intense beams of light for use in scientific experiments. Electrons travelling at close to the speed of light under ultra-high-vacuum conditions have their path changed by powerful electromagnets. Changing the path of the electrons produces synchrotron light, which is about a million times brighter than the sun.

> *"The usefulness of synchrotron light is limited only by our imagination"*
>
> *Professor Emeritus Sir Gustav Nossal AC CBE FAA FRS*

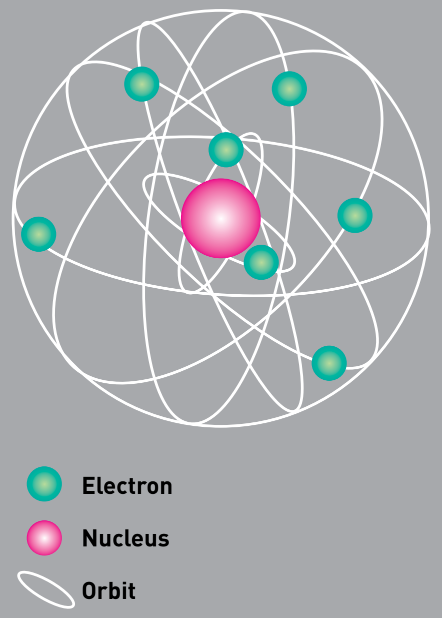
Facility Map

1. Electron Gun

Electrons are generated inside an electron gun by heating a barium compound cathode to ~ 1000°C. Bunches of electrons are accelerated away from the cathode surface and out of the gun using 90,000 volts.

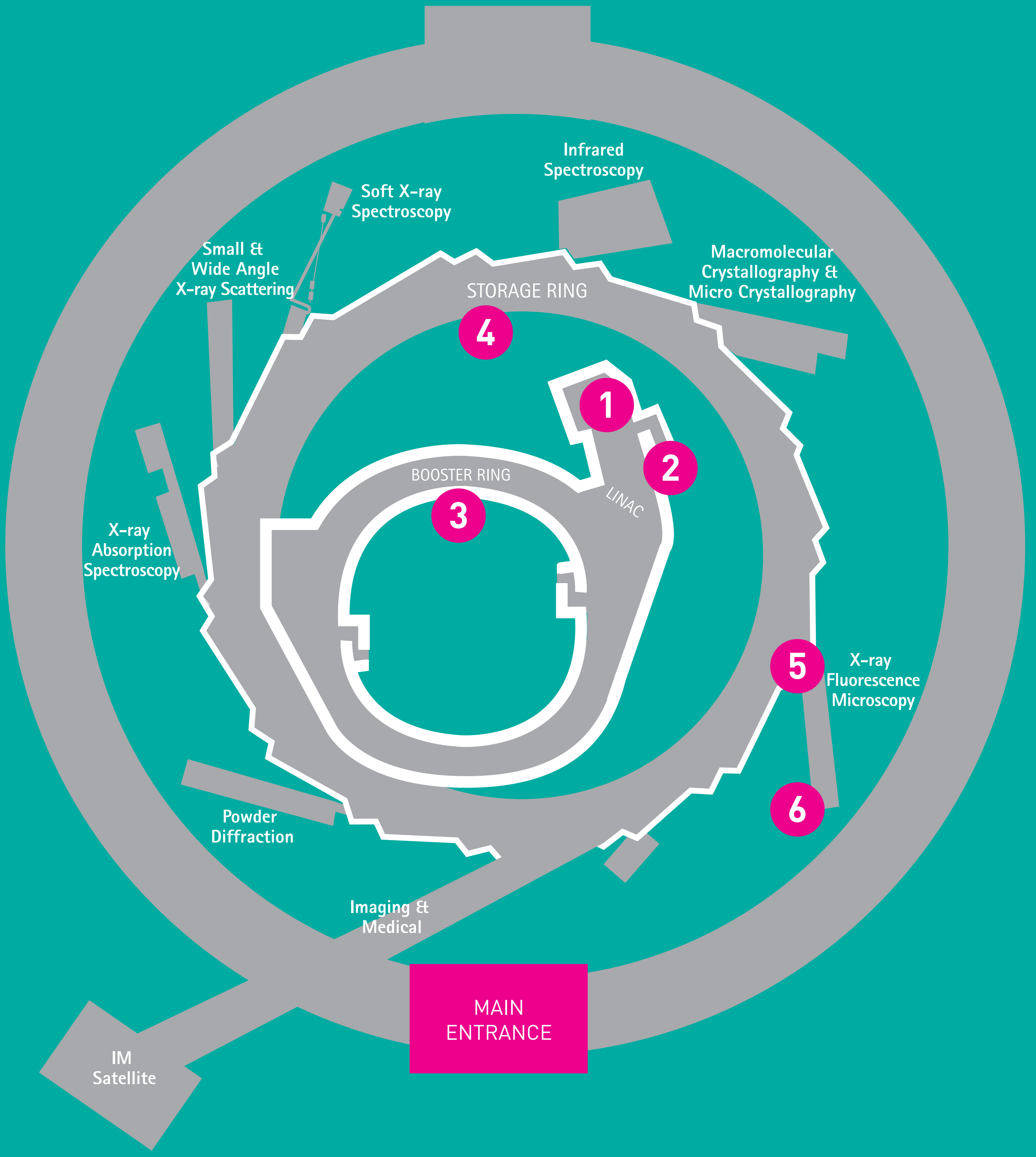
What is an electron?

An electron is a stable subatomic particle with a negative electric charge. Electrons surround the nucleus of an atom, and are extremely small and unimaginably light. Electricity is the flow of electrons through a conductor such as a metal wire.



2. Linear Accelerator (Linac)

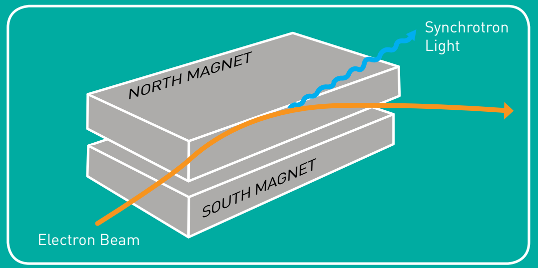
In the Linac, the electrons are accelerated to 99.9987% of the speed of light. They exit the linear accelerator with 100MeV of energy. The energy used to accelerate the electrons comes from a radio frequency (RF) current of 3GHz. Radio frequencies are part of the electromagnetic spectrum, just like infrared light, but they have lower energy levels and therefore longer wavelengths. The spacing of the electron bunches matches the wavelength of the RF current, thus ensuring that the electrons receive a 'push' through the regions where the RF current is applied.



3. Booster Ring (synchrotron)

The electrons are transferred from the Linac to the Booster Ring, where their energy is boosted to 3GeV using more RF energy.
In the Booster Ring, dipole electromagnets force the electrons to adopt an almost circular path. The electrons complete approximately 1 million laps in half a second, before passing into the Storage Ring.

Bending Magnet



4. Storage Ring

In the Storage Ring, electrons circulate at a constant energy for approximately 30–40 hours, and continuously generate intense synchrotron light. To ensure the number of electrons circulating remains nearly constant, they can be topped up by injecting more into the ring approximately every two minutes.
An electron will complete around 1.4 million laps of the Storage Ring every second.

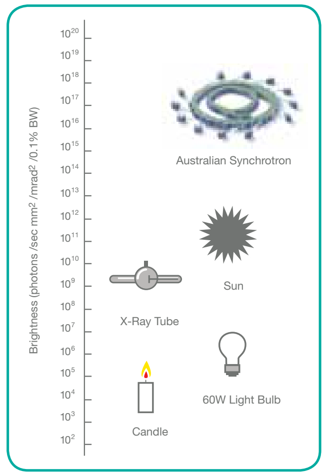
5. Beamlines

The synchrotron light - created by bending the path of the electrons through magnetic fields - is then channelled from the Storage Ring down long pipelines, called beamlines, so that scientists can utilise it for research. Each beamline includes different types of filters, mirrors and other optical components that prepare the light for use in a range of different scientific experiments.

6. End Station

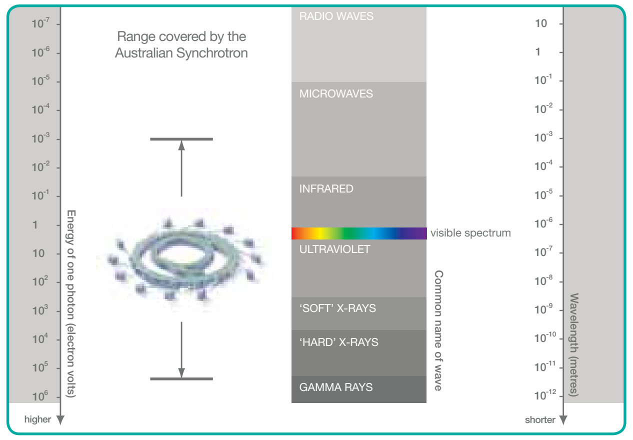
At the end of each beamline is an End Station – a laboratory where the synchrotron light interacts with a sample. Detectors positioned around the sample measure how the light is transmitted, emitted, scattered or diffracted (depending on the experiment) by the sample. Researchers use this information to determine the composition or atomic structure of the sample, or to create a map-like image of the sample.

What makes synchrotron light so special?



Brilliant: Synchrotron facilities allow us to focus a lot of light over a narrow wavelength range in a small number of directions over a small area in a very short amount of time. This means for a particular experiment, synchrotron light can be extremely intense. This intensity allows researchers to collect more detailed and accurate information in faster times than with conventional equipment, and can also reveal information that cannot be seen using any other methods.

Wide spectrum: The light emitted covers a continuous, wide range of wavelengths simultaneously. Much of the light emitted is outside the visible spectrum, from infrared light to x-rays. The kind of light produced depends on the energy of the electrons. Electrons going around a curve with lower energy might produce visible light; with higher energy they might produce x-rays. Infrared light, visible light and x-rays are all forms of electromagnetic radiation, but infrared light has lower energy levels than visible light and x-rays have much higher energy levels than visible light.



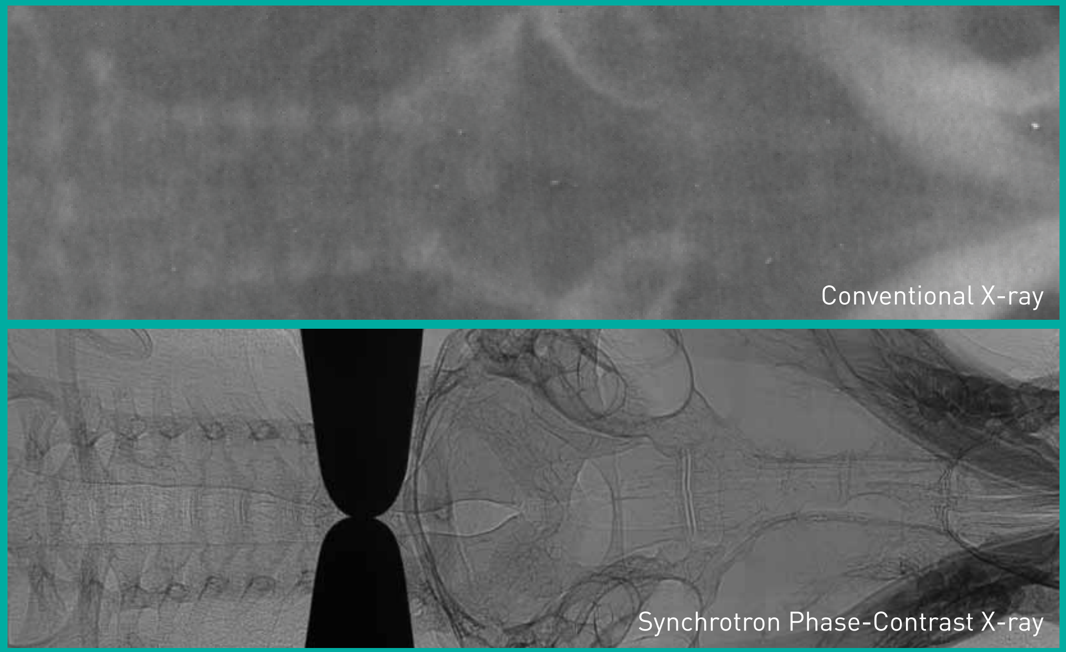
Tuneable: A single wavelength or range of wavelengths can be specifically selected for each synchrotron experiment.

Pulsed: The light is emitted in extremely short flashes. This means that researchers can watch changes in a sample over very short periods of time (even nanoseconds) or take movies of very fast reactions occurring on a very small scale.

Collimated: The synchrotron light beam is precisely focused, resulting in a very small divergence which allows extremely small areas of a sample to be investigated.

Polarised: Synchrotron light is highly polarised, which improves sensitivity when conducting experiments.

Visualisation of anatomical detail

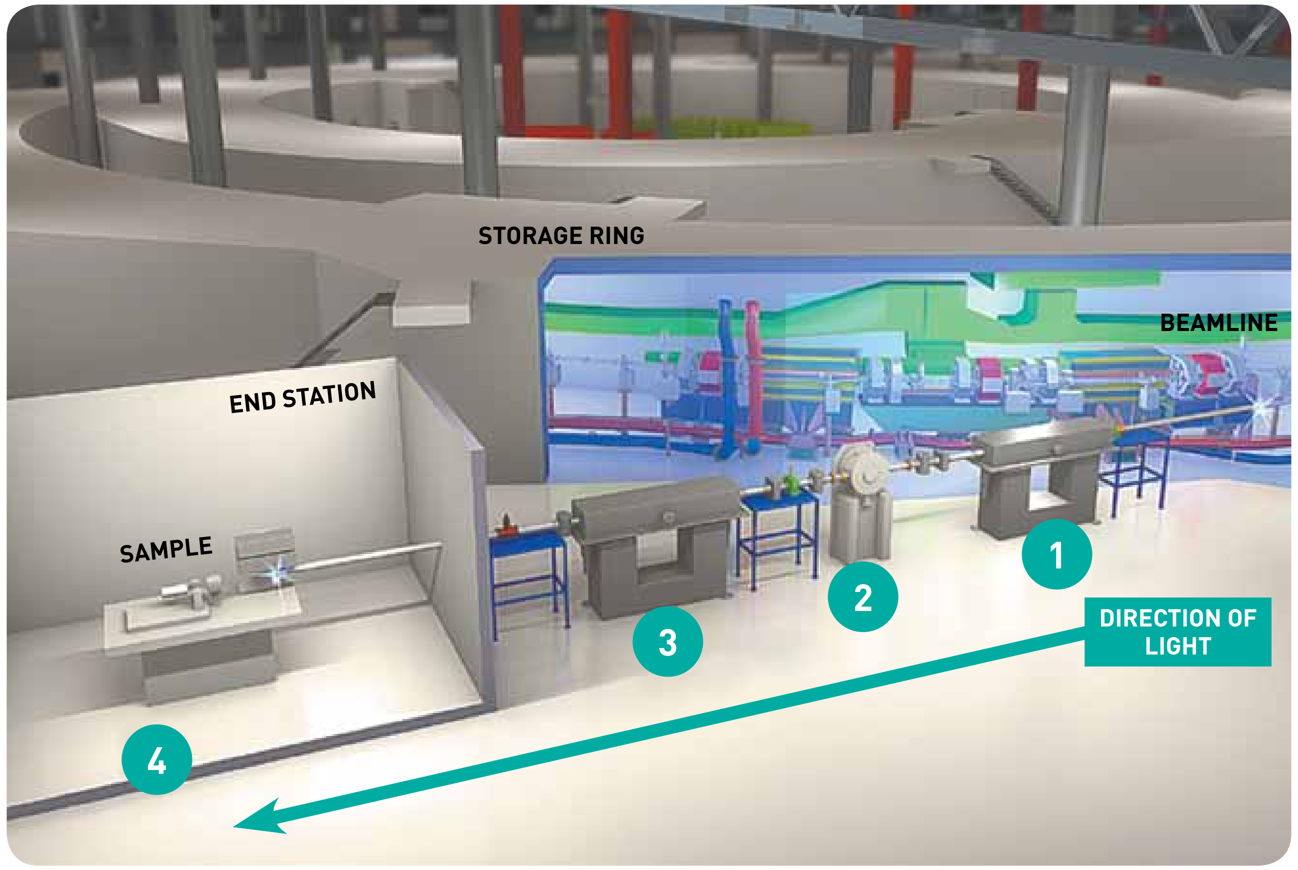

Conventional X-ray

Synchrotron Phase-Contrast X-ray

Parsons et al, J. Anat. (2008) 213, pp217–227

What can you do with this powerful tool?

Example: Using Synchrotron Light for Protein Crystallography



1. **Vertically collimating mirror:** Narrows the beam to 500 microns or ½ mm (one micron = one millionth of a metre)
2. **Double crystal monochromator:** Selects the appropriate wavelength of light for the experiment. The best diffraction results are achieved when the wavelength of the x-rays is similar in size to the interatomic distances being investigated. An energy range of 5keV-20keV is equivalent to wavelengths of 2.5Å – 0.6Å (1Å = 0.1nanometers or 1 billionth of a meter)
3. **Vertically focusing mirror:** Focuses the beam to converge at the sample and maximise the amount of light hitting the sample.
4. **End Station (laboratory):** Robots are used to load the samples in the End Station. When the beam is turned on, x-rays hit the sample and a detector collects the light scattered from the sample. The diffraction pattern that results from the scattered light reveals the molecular structure of the sample. More than 100 billion photons hit the sample each second within an area of 250 microns x 200 microns. Samples can be less than one micron across, or around one-hundredth the diameter of a single human hair.

Applications of Synchrotron Techniques

Synchrotron light can be used for a very wide range of applications, depending on the optical components of a particular beamline. Research is conducted across all stages of the innovation chain, from concept to market.

Synchrotron techniques provide information with much better detail, quality and accuracy than conventional methods. Added to that, these results are achieved in much shorter time frames, making synchrotron studies an invaluable tool to researchers, industry and the community we are all part of.

Case Study 1 - Drug design and the assassin protein

New ways to fight disease

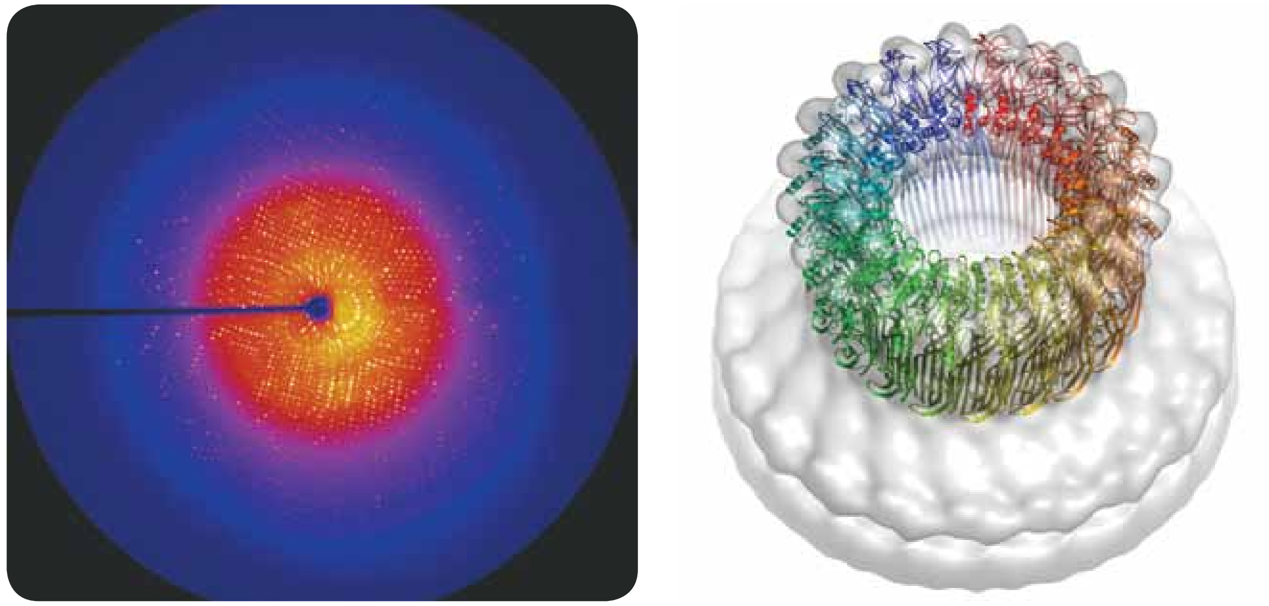
Developing a new prescription drug is an expensive long-term proposition involving laboratory research, approved animal trials, clinical studies and strict regulatory requirements that aim to protect the consumer. Synchrotron techniques are an essential part of the process, helping researchers to quickly screen hundreds of potential drug candidates and select the best ones for further work.

Professor Michael Parker from St. Vincent's Institute of Medical Research in Melbourne says that "all major biotech and pharmaceutical companies actively developing drugs in Australia now use or aspire to use the Australian Synchrotron".

Scientists are also using synchrotron techniques to examine the innermost workings of the immune system.

The 'assassin protein' perforin is an important part of our immune defences. It punches holes in cancer cells and cells that have been hijacked by viruses. The holes allow toxic enzymes produced by our immune system to enter and destroy the rogue cells. If perforin isn't working properly, the body can't fight infected cells. Defective perforin also sometimes marks the wrong cells for elimination.

Researchers used microcrystallography at the Australian Synchrotron to help reveal how the thin, key-like perforin molecules form a circle to penetrate the cell membrane. This information will speed up the development of new drugs for life-threatening diseases such as cancer.



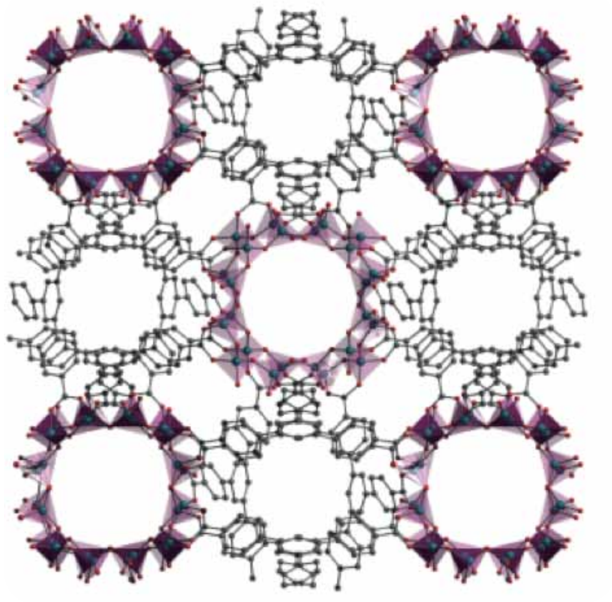
X-ray crystallography produces diffraction patterns like this one (above left). Scientists use computers to analyse and manipulate the x-ray diffraction information to reveal structures such as this perforin pore (above right).
Law et al, Nature 468 447-451 18 November 2010

Researchers are also using the Australian Synchrotron to help them:

- Test potential new treatments for cystic fibrosis
- Devise 'microbeam radiotherapy' treatments that could destroy cancerous tumours without seriously affecting normal tissue
- Develop more effective treatments for diseases such as HIV-AIDS, tuberculosis, malaria and diphtheria
- Enable earlier detection of diseases such as multiple sclerosis and rheumatoid arthritis
- Improve the success of organ transplants
- Learn more about the body's immune system and use this knowledge to improve our health
- Identify and test new ways to deliver pharmaceutical drugs to specific parts of our bodies, to increase efficiency and minimise side-effects.
- Resolve protein crystal structures in minutes rather than weeks or months using cutting edge software, AutoRickshaw, to process AS data

Case Study 2 - Room inside

Improving our environment



An area the size of a football field in a single gram? It sounds impossible, but it isn't.

An exciting new kind of material called a metal-organic framework (MOF) has a periodic, open structure that creates internal surface areas as high as 10,000 square metres per gram of material. With walls that are only a single atom in thickness, a MOF can be up to 80-90% empty space – leaving plenty of room for storage of huge quantities of gaseous fuels or greenhouse gases.

MOFs have big potential for use in the automotive and energy sectors, including storing hydrogen and methane to power vehicles and capturing carbon dioxide from coalfired power stations. Using MOFs for on-board methane storage in natural gas-powered vehicles, for example, could deliver a driving range comparable to petrol-powered vehicles – with dramatically reduced greenhouse emissions and running costs.

Scientists are using powder diffraction and microcrystallography techniques at the Australian Synchrotron to identify the best MOFs for particular uses, such as storing fuels and greenhouse gases, and applications in industrial catalysis and medical diagnosis.

Sumida, K et al, J Am Chem Soc2009 ja-2009-072707

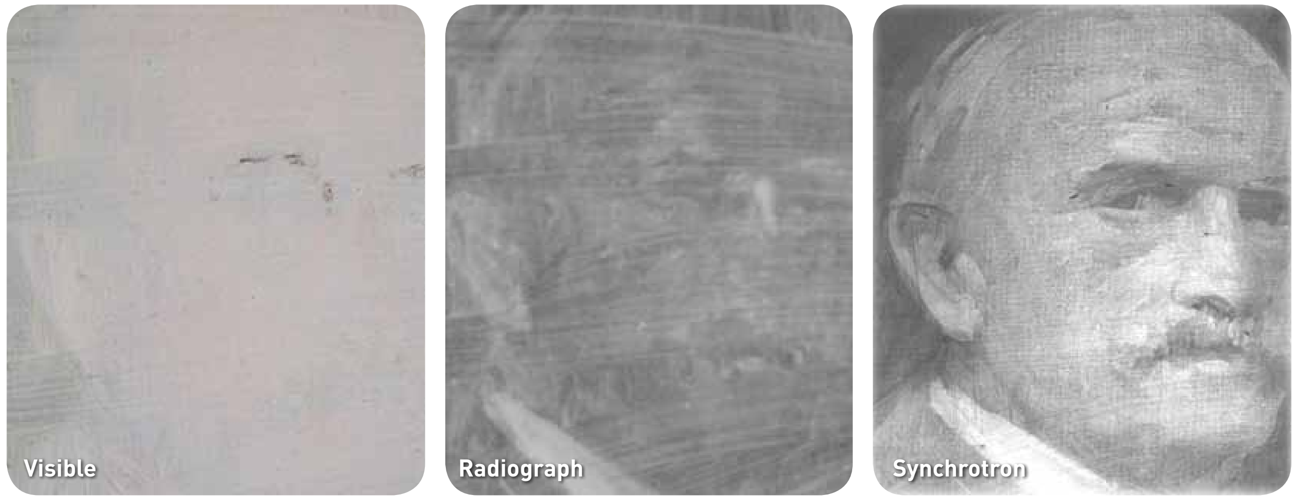
Researchers have also used the Australian Synchrotron to help them:

- Investigate how tiny plankton in the world's oceans might respond to climate change, and how this could in turn affect global conditions
- Develop new construction materials such as 'green cement', which uses power station waste as a base material and cuts carbon dioxide emissions by 80 percent
- Examine how organic matter in soils influences how metals and pesticides are absorbed into the soil
- Identify the aluminium mineral responsible for a series of major deaths in fish populations in northern NSW
- Study the behaviour of gas molecules that contribute to global warming or damage the ozone layer
- Specifically identify lead from leaded petrols used in the past as the main cause of high lead levels found in homes in Western Sydney

Case Study 3 - Picture this!

Safeguarding our heritage

The details of a hidden painting by a famous Australian artist were revealed recently by art experts and scientists using the Australian Synchrotron. They were able to peer beneath the layers of white lead paint that Arthur Streeton had used to cover up a rare self-portrait.



Similar techniques are helping us to preserve historical documents, works of art, buildings and other physical objects from our own past and from ancient civilisations. These physical objects are often fragile and require careful handling to ensure their continued preservation.

Synchrotron techniques are non-destructive and can rapidly provide details of the chemical composition of materials. For example, knowing which chemicals are present, and where, in paint pigments and surface treatments provides valuable information that helps experts restore paintings or keep them in good condition – or potentially even confirm an artist's identity in cases where this is unclear.

The National Gallery of Victoria is working with CSIRO and the Australian Synchrotron to develop ways to use X-ray Fluorescence Microscopy (XFM) to investigate materials used in artworks from the NGV collection. XFM maps the presence and location of trace metals in a wide range of samples and provides chemical information as well.

http://www.rsc.org/chemistryworld/News/2012/March/hidden-art-painting-restoration-x-ray-arthur-streeton.asp
Howard et al, Analytical Chemistry 84 (7):3278-86 3 April 2012

Researchers have also used the Australian Synchrotron to help them:

- Halt the degradation of 19th century parchments, and documents and artworks dating from the Middle Ages to the early 20th century
- Create a pigment 'fingerprint' library to help curators, conservators and collectors answer questions about who painted a particular art work or when it was painted
- Link ochres used on Aboriginal artefacts to the mine sites where the ochres originated, shedding new light on cultural exchange networks and trade relationships
- Study Aboriginal rock art from Queensland, and paint and plaster samples from Mayan buildings in Honduras
- Examine and characterise 20th century painting materials and their degradation in humid environments
- Investigate the chemistry and manufacture of faience, a blue-green material used in ancient Egyptian artefacts.

Case Study 4 - Mineral magic

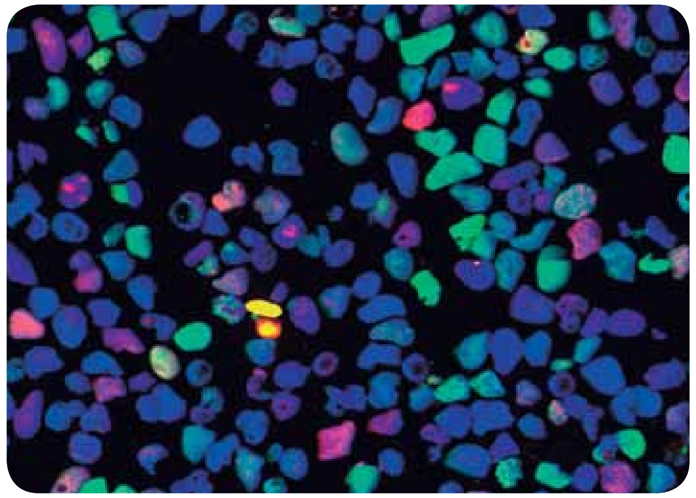
Improving efficiency and environmental impact

Real-time *in situ* analysis of mineral processing reactions at the AS is helping to position Australia's massive mining industries for the years ahead: cutting carbon emissions, improving environmental management, raising productivity and extracting valuable metals from previously discarded low-grade ore.

For example, CSIRO scientists are conducting real-time *in situ* studies of high-pressure acid leaching of nickel ores, scale formation and leaching in bauxite (aluminium ore) processing, molten salt electrowinning of titanium and sintering of iron ore – and investigating how impurities affect the efficiency of mineral extraction processes such as flotation.

Synchrotron techniques are also helping CSIRO to improve bioleaching (bacterially-assisted leaching) methods for extracting metals such as copper from low-grade sulphide ores, overburden and waste from current mining operations. Bioleaching is potentially less expensive, less intensive and more environmentally-friendly than traditional methods such as high-temperature processing. It has been used to extract copper on a commercial scale from some sulphide minerals, but other minerals are proving more difficult.

A combination of synchrotron techniques is providing new information on how jarosite minerals cause problems in bioleaching systems, or lead to groundwater contamination as a result of acid and heavy metal release from acid mine drainage environments.



Synchrotron image showing distribution of titanium (blue), niobium (green) and thorium (red) in ilmenite, and iron titanate ore. Ilmenite sample courtesy of Peter Kappen, La Trobe University; image from XFM beamline and CSIRO collaborators Chris Ryan, Robin Kirkham and Gareth Moorehead.

> *"For us, the Australian Synchrotron provides a world-class facility without the need to take large pieces of tailor-made equipment overseas."*
>
> *Dr Nicola Scarlett, CSIRO x-ray diffraction expert*

Researchers are also using the Australian Synchrotron to help them:

- Obtain 3D pictures or 'maps' of nanoscale details much faster and with one thousand times more detail than was previously possible – to assist the search for fresh mineral reserves and the development of more efficient and environmentally sustainable processing methods
- Provide micron-scale information about how composition varies across petroleum reserves to improve utilisation of these important reserves
- Show where arsenic is located in nickel sulphide ores, to help improve processing efficiency and avoid potential environmental problems
- Identify a potential treatment for residues from bauxite processing before they are deposited as tailings
- Resolve geological controversy surrounding a rare type of volcanic rock, leading to valuable new insights into the Earth's early geological processes
- Recreate the environmental conditions experienced on the icy moons of Jupiter and Saturn and investigate their extraordinarily complex geological features
- Improve the processing of bentonite clays, which are used in geosynthetic barriers to stop metals leaching out of municipal and industrial landfill sites