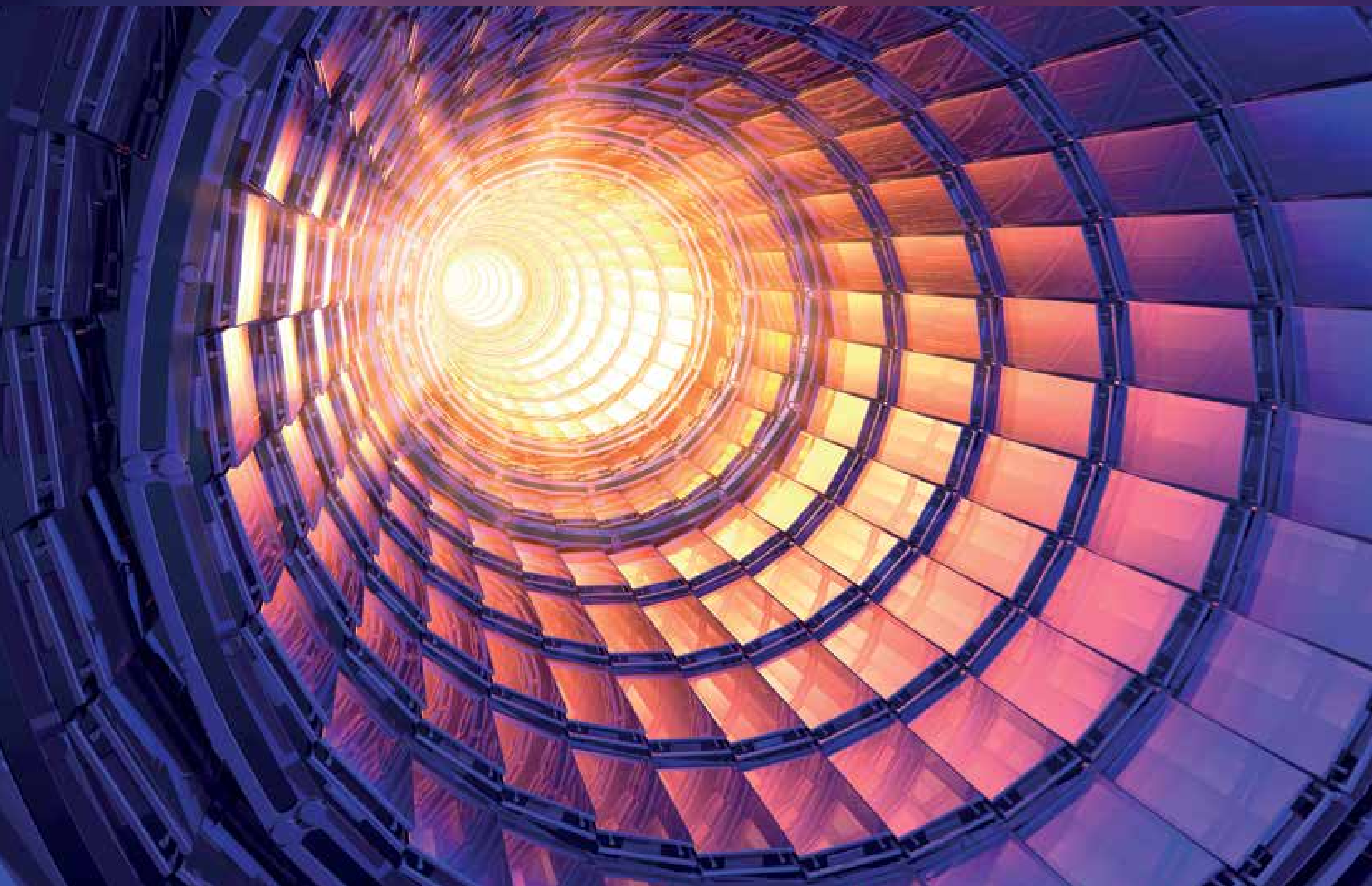
Discovery Machines

Accelerators for science, technology, health and innovation



Australian Academy of Science

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In memory of Dr David Weisser, who died on the 24th of July 2015. David played an enormous role from 1971 to 2015 in developing the ANU Heavy Ion Accelerator Facility to be a world benchmark for performance, reliability and innovation. The Australian and international accelerator community will miss his expertise, encouragement, friendship and guidance.

Expert Working Group

Co-Chairs
Professor David Hinde FAA
Professor Keith Nugent FAA

Members
Professor Elisabetta Barberio
Professor Eva Bezak
Associate Professor Mark Boland
Professor David Cohen
Professor Rob Elliman
Professor Keith Fifield
Dr Lizbeth Kenny
Professor Andrew Peele
Professor Geoff Taylor FAA

Invited Contributors

Professor David Jamieson
Professor Andrew Stuchbery

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Future Science

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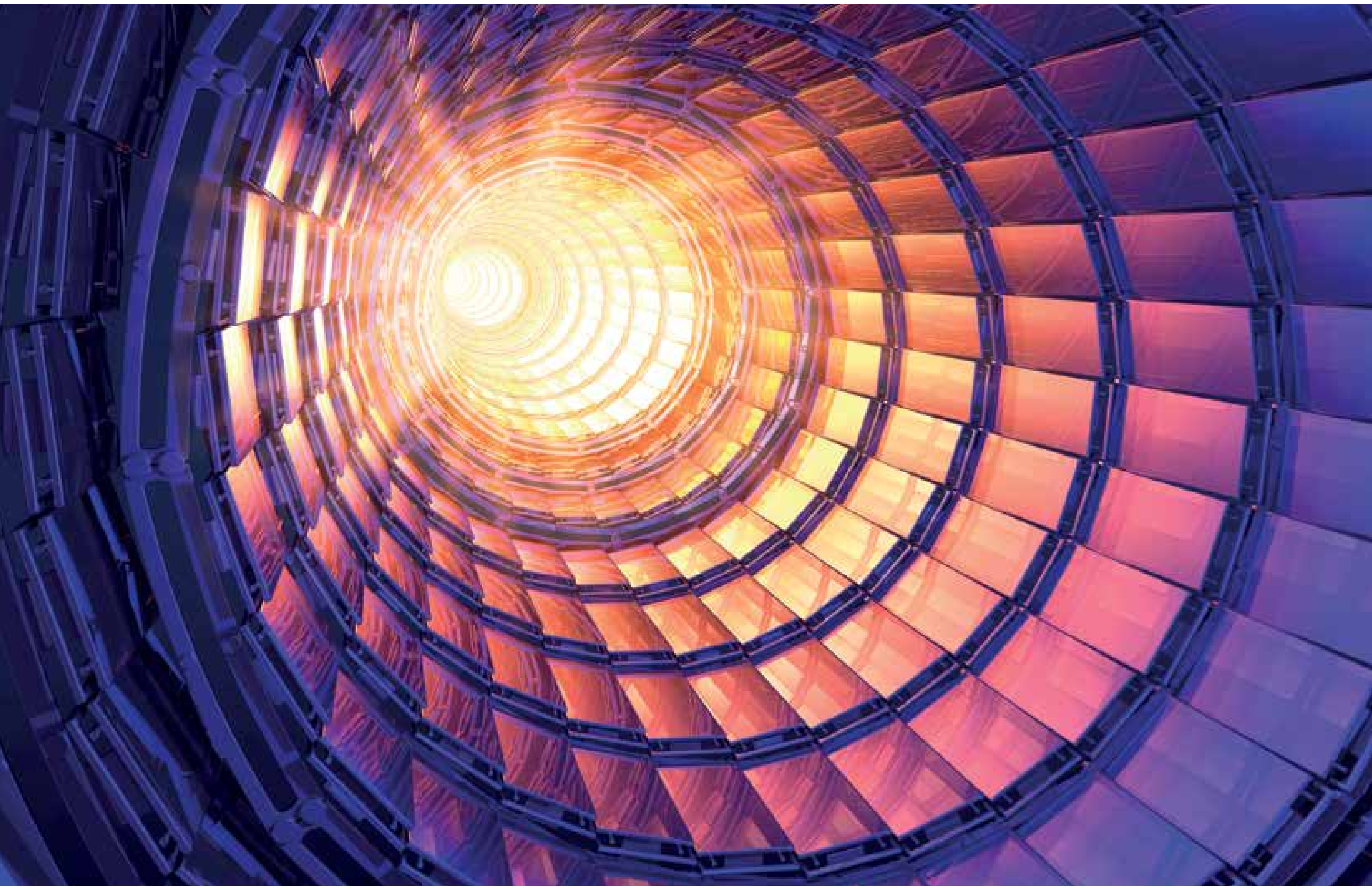
Accelerators for science, technology, health and innovation



Australian Academy of Science

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Foreword

The Australian Academy of Science is proud to have had the opportunity to partner with the Defence Science and Technology Group (DSTG) to produce a series of science foresighting reports examining likely medium-term developments and advances, in a range of enabling, cross-disciplinary fields of science. These reports offer insights into emerging science and technology applications and provide guidance on how Australia can better position itself to reap the economic and social benefits on offer.

These reports would not be possible without the expertise of Academy Fellows and other leading scientists who form Expert Working Groups to review the current literature and emerging scientific directions, and collate them in these reports in a way that is accessible to an informed, general audience. In this way, these reports are consistent with the Academy's mission of promoting scientific understanding.

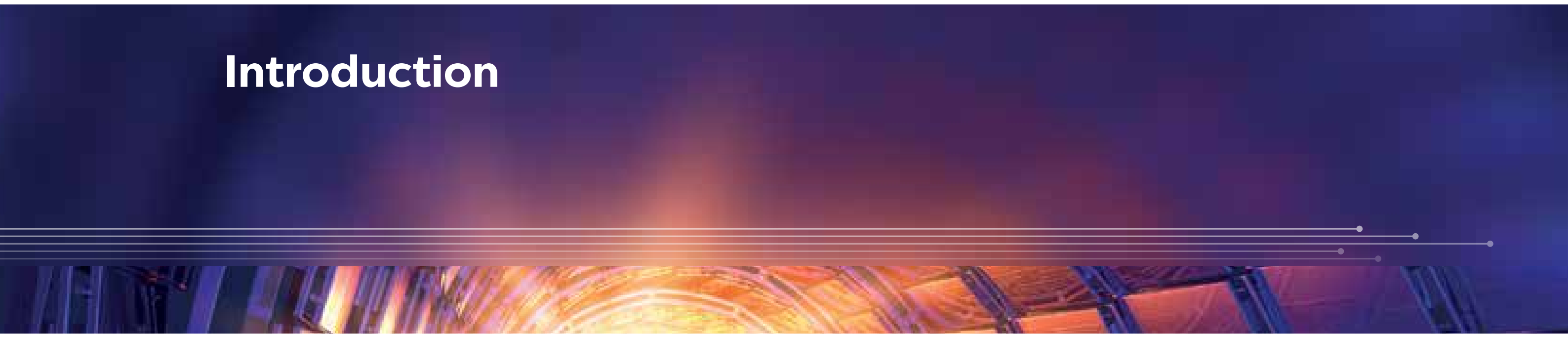
Particle accelerators and the science that underpins them are now ubiquitous—every hospital and many medical clinics have X-ray machines. Some homes may still have Cathode Ray Tube televisions. Advanced accelerators also underpin a diversity of industries and scientific endeavours from discovery science to applications in medicine, energy and environment, among others. Accelerators are also major drivers of international scientific collaboration allowing mutual exchange of knowledge and technology, and development of specialised technical skills.

This report, *Discovery Machines—Accelerators for science, technology, health and innovation* provides an overview of the future capacities, capabilities and applications of Accelerator science in Australia, and to the extent possible, identifies scientific opportunities that developments in Accelerator science may offer over the next 10 to 20 years. The feasibility of investing in the technology, infrastructure and expertise needed for a national capability in Hadron therapy for cancer treatment has been particularly considered.

The Academy is very appreciative of the contributions made to this report by the Working Group members and other experts. The Academy also thanks the Defence Science and Technology Group for providing financial support to prepare this document.

Andrew Holmes AM PresAA FRS FTSE
President
Australian Academy of Science

Introduction



Accelerators play a critical role in Australia's research and development capacity, and in the everyday lives of all Australians.

They underpin many scientific fields, from fundamental physics to climate science. From the first low-energy accelerators more than a hundred years ago, which showed the existence of electrons, to high-energy accelerators prising open the atomic nucleus to reveal its constituent neutrons and protons and their constituent quarks, accelerators have played a key role in some of the most significant scientific discoveries of our time. With every step forward in understanding, new questions arise, calling for new and improved accelerator capabilities to answer them.

Most of the 30 000 accelerators operating in the world today are used in medicine and industry, contributing to our current and future health and technologies. In the industrial realm, accelerators have made groundbreaking contributions to semi-conductors, microchips, wastewater treatment and solar photovoltaics. Many of these contributions have occurred relatively recently, indicating that accelerator applications may only be at an early stage of their contributions to innovation and discovery.

Accelerators are also essential in modern medicine. X-ray imaging, used routinely, is based on small electron accelerators. In radiation oncology centres across Australia, more than 170 linear accelerators are used to destroy tumours, while radioisotopes produced by proton beams are used every day for patient diagnoses.

Large accelerators are complex and often expensive, but the discoveries and industry developments that flow from them repay the initial investment many times over. Australia's largest accelerator facility, the Australian Synchrotron, hosts more than 4000 researchers per year and operates more than 900 experiments from across Australian industry and academia annually, developing core expertise that enhances the national skills base in new technologies that are now used widely in cutting-edge manufacturing and engineering. While larger accelerators dominate the public awareness, smaller accelerators are surprisingly ubiquitous, found in hospitals, universities and research laboratories across the country.

Accelerators are also major drivers of international scientific collaboration across borders and disciplines. Larger accelerators, which often operate as national or international facilities, bring researchers together from all over the world. Accelerators are the standard-bearers for science as a global endeavour, showing the extraordinary things that can be achieved when science transcends borders, sectors and scientific fields.

Australia has been part of the accelerator revolution from the beginning, through physicist Sir Mark Oliphant, one of Australia's most respected scientists. In the 1930s his experiments revealed the nuclear fusion reactions that power the stars, and he invented and then built the first synchrotron accelerator. He created Australia's first accelerator capability at the Australian National University in the 1950s. Australia is now home to several major accelerator facilities, including the Australian Synchrotron and the Australian Nuclear Science and Technology Organisation Centre for Accelerator Science, as well as the Australian National University's Heavy Ion Accelerator Facility. They each make Australia a world player in their respective fields. Australian researchers are also significant users at some of the world's biggest accelerator institutions, including CERN in Switzerland, and the Linac Coherent Light Source operated by Stanford University in the US, the world's first X-ray free electron laser.

However, Australia's accelerators are currently tip-toeing on financial quicksand. In the absence of secure, long-term funding, we risk losing many of the gains that we have made so far, in both infrastructure and expertise, and slipping backwards at a time when the rest of the world is surging forward. The Clark Research Infrastructure Review of funding for national research infrastructure is a positive step.

Anticipated developments in accelerator technology and science in Australia and overseas are pointing to an exciting future. We have the promise of new accelerator technologies reducing size and cost. Thanks to accelerators, we have new techniques to probe the natural world, and the potential for cleaner fossil fuel emissions and safer nuclear power. And now we have X-ray lasers so powerful that they can give us atomic-scale snapshots of the progress of chemical or biological reactions.

This report *Discovery Machines—Accelerators for science, technology, health and innovation* reveals the remarkable extent to which accelerators have enabled so many of the discoveries that shape our lives, industries and economy today, and how they continue to be a fundamental part of Australian and global science.

It provides an overview of accelerators: how they work, how they are used and examples of some of the myriad ways in which they continue to improve our day-to-day lives.

It examines Australia's position in the global arena of accelerator science. At our large-scale national facilities, Australian researchers have access to world-leading accelerator technology, while the general community benefits from a large number of small-scale accelerators that are used in medicine, resource management (e.g. water) and environmental sciences. Australian scientists are also strongly engaged at international accelerator facilities, including the Large Hadron Collider at CERN, where they have contributed to some of the most groundbreaking discoveries of our time, notably the Higgs boson.

Accelerator science is very knowledge intensive, requiring considerable investment in education and training by those who build, operate and use accelerators. With further development of accelerator expertise, Australia can become a stronger regional resource in the growing field of accelerator applications.

This report looks to the future and the developments that lie over the horizon. Australia has played a strong role in the accelerator arena for a long time, but we have much to do if we are to maintain and enhance our position. Our facilities are world class, but it will take considerable effort and investment to ensure they remain this way, and to ensure that Australia is well positioned to be a key player in new developments and applications as they emerge.

This report gives a list of recommendations that will help to make this happen. These recommendations aim to secure and strengthen our existing accelerator infrastructure, address gaps in our accelerator capacity and enhance planning for future advances, including ensuring we have a scientific workforce trained in the development and application of accelerator technology.

Recommendations

This report recommends that:

1. State and federal health departments work together to assess the value and the feasibility of investing in the technology, infrastructure and expertise needed for a national capability in **hadron therapy for cancer treatment**. Such a capacity would potentially have multiple benefits, including improving health outcomes and reducing overall cancer management costs, especially for patients who have no other treatment option, and establishing Australia as a regional capability centre in hadron therapy.
2. The recommendations of the Clark Research Infrastructure Review are implemented in a way that ensures **ongoing operations funding** for Australia's existing world class accelerator infrastructure through NCRIS or any future program responsible for research infrastructure. Furthermore, that a national funding program for large-scale infrastructure projects be established with the capacity to keep Australia's national accelerator infrastructure up to global standard.
3. Australian universities develop an **outstanding program in accelerator R&D** to attract high-quality PhD students. This program will improve Australia's accelerator capability, support training in the specialised technical skills needed to exploit new investment in accelerator technology, and position the nation to exploit opportunities opening up in this critical area.
4. Dedicated funding be provided through the Australian Government's proposed International Science Engagement Strategy to allow Australian accelerator researchers and research facilities to **partner with international facilities**, such as the proposed US$10 billion International Linear Collider and the Linac Coherent Light Source in California. This will support the development of high-tech local industry.
5. Current and future bodies responsible for development and operation of Australia's major national research infrastructure **liaise closely with the Australian Collaboration for Accelerator Science and relevant National Committees of the Australian Academy of Science** for advice and recommendations on issues relating to strategic directions, funding priorities and technical issues pertaining to accelerator facilities and capability in Australia.

1 Accelerators and their applications

1.1 What are accelerators?

Accelerators are machines that use electromagnetic fields to accelerate charged particles, such as electrons or protons, to high speeds—sometimes close to the speed of light. They produce a beam of particles of the same kind, all having the same energy and travelling in the same direction.

The progenitors of today's accelerators were primitive vacuum tubes—the pinnacle of technology of their time. In 1895, German physicist Wilhelm Röntgen, using a vacuum tube for curiosity-driven research into electrical phenomena, discovered X-rays. This world-changing discovery earned him the first Nobel Prize in Physics, and started a connection between electron accelerators and X-rays that continues to produce important applications of enormous benefit to humanity.

The basis for many modern particle accelerators were established in the 1930s by Cockcroft and Walton at the Cavendish Laboratory in Cambridge in the UK, by Lawrence in Berkeley, California, and by Oliphant in Birmingham in the UK. These resulted in two families of accelerators: linear accelerators and circulating accelerators.

In linear accelerators—often called linacs—the beam is accelerated in a straight line, passing through the accelerator once, as in Cockroft and Walton's electrostatic accelerator. Linear accelerators can produce continuous beams of particles or pulsed beams, but the accelerated beam particles are only used once. Linear accelerators are particularly suited as heavy ion accelerators, producing beams of charged atoms (ions) of any chemical element.

In circulating accelerators, such as cyclotrons and synchrotrons, the particles pass through the accelerating structures many times in a circular fashion, as in Lawrence's first four-inch diameter cyclotron. This allows the generation of higher energies, and generally results in pulsed beams. In accelerators such as the Australian Synchrotron, the particles can circulate many millions of times. High-intensity photon beams, including brilliant X-ray beams for research, are continually generated by the circulating particles.

Accelerators can be used differently, depending on the application. In many applications, the accelerated particles directly bombard a stationary target. This is the case in the heavy ion accelerators that are used in materials research and modification, in single atom counting by accelerator mass spectrometry, and in medical radiation treatment such as hadron therapy.

A very important application of accelerators is to generate secondary radiation, which is itself the desired product. This is the case in medical X-rays produced by accelerated electrons, synchrotron light sources with a broad range of applications, and accelerator-driven (spallation) neutron sources.

To produce the highest energy collisions for research, the beam of accelerated particles is collided with another beam travelling in the opposite direction. This technology is used in high-energy physics.

1.2 What are accelerators used for?

Although accelerators were originally developed for research in physics—where they still play a central role—their use today is broad and heavily intertwined with the day-to-day work of millions of people. The science and technology of accelerators has developed at an extraordinary pace and now has a major impact on our economy, health and wellbeing.

An Ingenuity model PET/CT scanner. Image courtesy Philips Healthcare.

Accelerators are essential to modern science, industry, defence and medicine. Particle beams of the right energy and intensity can interact with a wide range of materials in many useful ways, ranging from killing cancer cells within humans to implanting ions in semiconductor wafers to make solar panels, to scanning incoming freight for illegal drugs or keeping pathogens out of the food and water supply. With a wider span of applications than almost any other scientific tool today, they are providing deep insights into nature across diverse disciplines, and are recognised internationally as being critical for the advancement of science, health, technology and innovation.

Accelerators are thus an essential component of national infrastructure, providing quantitative knowledge and capabilities for many fields. Although there is a wide diversity of types of accelerator and applications, as discussed below, accelerators themselves have overlapping technological foundations, making the nation's accelerator infrastructure a natural grouping.

i. Industry

The information and telecommunications revolution is built on accelerator technology; one of the main industrial uses of accelerators is in the production of the semiconductors that are ubiquitous components inside almost all electronics.

Semiconductors are usually based on silicon or sometimes germanium that has been 'doped'; that is, it has had precisely controlled impurities added to the silicon. This changes the electrical properties of the material so it conducts electricity in the desired way.

Ion implantation is particularly effective and reliable for silicon doping; a beam of ions of a particular element is fired from a particle accelerator into a silicon wafer. The ions stop in the silicon crystal lattice at a specific depth that can be controlled by the energy of the beam. Ion implantation technology is more precise than previous diffusion doping methods and yields better and cheaper semiconductors. For example, the fabrication of a typical microprocessor involves 40–50 ion implantation steps that are variously used to dope the semiconductors. All digital electronics are now dependent on ion implantation using accelerators. Some 10 000 heavy ion accelerators are used worldwide to dope the silicon or germanium in computer and mobile phone chips, in memory chips and in fabricating high-performance layered silicon wafers widely used in photonics and high-end computing.

As well as ion implantation, many of the 20 000 accelerators used by industry worldwide are used for other types of materials processing and treatment, and for materials analysis. Electron-beam welding is used to join together extremely thin pieces of incompatible alloys, such as titanium and aluminium, with applications from the automotive to aeronautical and space industries. Electron-beam machining uses a higher powered beam to vaporise the metal and is used for precision cutting and etching metal surfaces, with machines able to drill 3000 holes per second.

In electron-beam heat treating, the beam is used to harden the surface of particular alloys, or to harden polymers such as carbon composites. This technique is proving particularly useful in the car manufacturing industry: X-ray-cured carbon composites can replace some steel parts and are much lighter. Electron or X-ray beams are used to cure materials impregnated into wood to make them stronger and more resistant to moisture, mould and fungi, reducing volatile organic compounds in furniture and offices.

The food industry also relies on accelerators for a number of applications, including irradiation for food preservation and for the manufacture of the cling wrap used to package many fresh foods. Accelerators are also used for curing inks, coatings and adhesives, and for surface sterilisation of medical devices and food packaging.

Improving solar cell performance

The main challenges in today's silicon solar cell industry are to increase the efficiency of converting sunlight into electricity, and to lower production costs. Commercial solar cells are made by the old technology of diffusing the doping atoms into the silicon to create the desired properties. One route towards achieving higher efficiency is the use of more sophisticated doping profiles that reduce contact resistance and maximise current collection. This is not easily achieved with conventional diffusion technology and researchers are now exploring ion implantation as an alternative, more flexible doping technique for solar cell manufacture.

Ion implantation uses heavy ion accelerators to bombard target materials with high-energy ions in order to modify their physical and chemical properties. The depth distribution of the implanted ions is determined by the ion energy, which can be controlled to achieve the desired result. The technique is used routinely in the silicon microelectronics industry but has not traditionally been used for solar cell manufacture due to higher cost.

This situation has recently improved through the availability of a new generation of high-throughput ion implanters specifically designed for solar cell production.
As a consequence, ion implantation now offers the potential for reduced cost of production, process simplification and improved cell performance. This has stimulated new research in this field, including a significant research effort at the Australian National University.

ABOVE: One route towards achieving higher efficiency is the use of ion-implantation as an alternative, more flexible doping technique for solar cell manufacture. Image credit: Shutterstock

ii. Environment

Accelerators have a number of applications in the environmental arena. Electron beams are being used to treat wastewater by removing organic and petrochemical pollutants, and to purify drinking water. They can also break down pollutants, such as oxides of sulphur and nitrogen, in the flue-gas emissions from coal-fired power plants.

In environmental research, ultra-sensitive heavy ion accelerators are being used to track soil erosion and deposition, and to map deep ocean currents. Tracking groundwater flows, such as in the Great Artesian Basin, is another application. This information is shedding light on past climatic conditions and helping inform models of the Earth's climate, as well as highlighting unsustainable resource usage. Heavy ion accelerators are also used to trace the content and source of particulate air pollution—an important application where environment and medical aspects can overlap.

iii. Medicine

Any person who has ever had an X-ray, undergone medical imaging such as a CAT scan, or been treated with radiotherapy has had a close personal encounter with a particle accelerator.

Almost as soon as X-rays and radioactivity were discovered in the 1890s, it was observed that radiation suppressed the growth of some tumours. Historical records suggest that the first cancer case was cured by these means back in 1898[1]. The first X-ray medical linear accelerator was produced in 1953, and it is now the primary device used in radiotherapy. These machines produce high-energy X-rays that can be directed and shaped to treat a cancerous tumour. About half of all patients diagnosed with cancer will undergo some form of radiotherapy.

The probability of tumour control increases with radiation dose; the higher the dose, the more likely a biological effect, namely tumour cell death, and the more likely a cure will be achieved. However, with increasing radiation dose there is increasing risk of damage to healthy tissues. As a result, the aim of radiotherapy is to deliver as high and as uniform a radiation dose as possible to the target tumour, while minimising the dose to surrounding healthy tissue.

Patients with tumours close to the surface of the skin may be treated with electron beam therapy.

1 Mould R.F. 1980, *A History of X rays and Radium*, IPC Business Press Ltd, London, UK.

Instead of the electron beam being used to generate X-rays, the electron beam is used directly on the tumour target. Electrons cannot penetrate far into tissue, as they rapidly lose energy, so this form of radiotherapy causes less damage to healthy tissues around the tumour.

A relatively novel and at present rapidly-expanding form of radiotherapy to treat cancer (originally proposed by R.R. Wilson in 1946) is hadron therapy, which uses beams of high-energy protons or heavy ions (both 'hadrons' in the language of physics) directed into the tumour. These are considered to have ideal characteristics for use in external beam radiotherapy because they achieve greater dose concentration in the tumour, and less radiation dose to surrounding tissues than X-ray radiotherapy. This makes hadron therapy particularly well suited to treat some forms of cancer of the eye, tumours that are difficult to treat surgically because of their location, tumours that are located next to radiosensitive organs, such as the brain and spinal cord, and those in the pelvic region, and childhood cancers in general.

In order to use protons and heavy ions for cancer therapy, they have to be accelerated to higher energies than the electrons that generate X-rays. Unlike radiotherapy X-rays, which are produced by linear accelerators, protons and heavy ions are accelerated in circulating accelerators: either cyclotrons or synchrotrons. During the past decade, the world has seen rapid expansion of hadron radiotherapy centres offering proton or heavy ion (primarily carbon) cancer radiation therapy. As of 2014, there were over 50 protons and heavy ion therapy centres in operation around the world. As many as 40 new facilities are proposed or under construction; some will combine both proton and heavy ion therapy facilities. By the end of 2013, more than 120 000 patients around the world had been treated with hadron therapy.

As well as improving the treatment of cancer, accelerators have contributed enormously to our ability to visualise tumours. The introduction of the computed tomography (CT) technology in the late 1970s was a major breakthrough in treatment planning, allowing doctors to clearly visualise the tumour and distinguish it from normal tissue. Magnetic resonance imaging (MRI) and positron emission tomography (PET) scanners soon followed, further enhancing our ability to diagnose and target cancer and other diseases, as well as image physiological processes in real time. PET scanners need special radioisotopes, which are produced by nuclear reactions, using cyclotron accelerators located at hospitals. Even a dental X-ray makes use of a small electron accelerator.

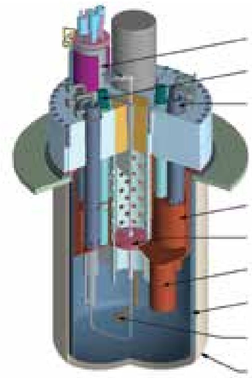
A GE medical cyclotron that accelerates protons to produce radioactive isotopes for PET imaging.
Image courtesy South Australian Health and Medical Research Institute.

iv. Medical research

Accelerators are also playing a vital role in medical research. Synchrotrons are now essential in the methods of structural biology leading to the development of new and more effective drugs. Synchrotrons are increasingly being used for medical imaging and the new methods of phase-contrast imaging are leading to insights into, for example, how a newborn takes its first breath. In the foreseeable future synchrotron radiation will be used for specialist treatment of cancers. Accelerators are also used to build nanoscale 'machines' known as micro-electro-mechanical systems or MEMS, which include microsensors. These are used in biotechnology, for example as biochips to detect hazardous chemical or biological agents, in microsystems for high-throughput drug screening and as disposable medical sensors used in surgery and blood analysis.

v. Energy

The use of accelerators in the energy arena has so far largely focused on reducing the environmental impact of energy generation, such as cleaning pollutants from the flue gas of coal-fired power plants. However, accelerator technologies are now being developed as possible drivers for safer and cleaner subcritical nuclear reactors, and to reduce the radioactive burden of high-level nuclear waste.



European MYRRHA is a flexible fast spectrum research reactor and the first prototype of a nuclear reactor driven by a particle accelerator. Image courtesy SCK•CEN. Used by permission.

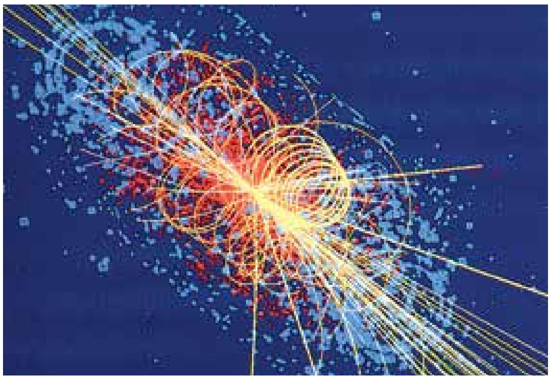
Belgium recently committed funding of $1.5 billion to build MYRRHA, the first prototype of a nuclear reactor driven by a particle accelerator[2]. In this reactor, the core does not contain enough fissile material to maintain the nuclear fission chain reaction by itself. Instead, the proton accelerator provides an external source of neutrons that sustain the reaction. This reactor is very safe, because cutting off the neutron supply stops the nuclear fission chain reaction within a tiny fraction of a second. It also has the potential to reduce the radioactive lifetime of existing nuclear waste by a factor of 100. These accelerator-driven systems are seen as one way to dispose of radioactive waste while generating power in a way that is safer than normal fission reactors.

Accelerators are also used to simulate high radiation conditions in energy-generation systems, allowing testing of critical materials for use in planned 'Generation 4' nuclear reactors, and for the international experimental fusion reactor ITER and its planned successor—the first demonstration fusion-power reactor, DEMO.

Minerals exploration also uses particle accelerators. Neutron logging involves the use of small portable neutron generators, used in conjunction with gamma-ray detectors to look for oil and gas deposits, as well as in prospecting for uranium and other minerals.

vi. Fundamental research

Accelerators play an essential role in probing the fundamental physics of matter, and how and where chemical elements were formed in the cosmos since the beginning of the Universe.



Protons collide at 14 TeV in this simulation from CMS, producing four muons. Lines denote particles, and energy deposited is shown in blue. Image courtesy CMS. © CERN

High-energy physics, or particle physics, aims to understand the underlying constituents of matter, and how they interact, at the deepest sub-atomic level. The recent discovery of the elusive Higgs boson in very high-energy proton collisions at the Large Hadron Collider at CERN captured the public's imagination and earned headlines around the world. Along with relativistic heavy ion collisions, particle physics probes the conditions just after the Big Bang. Because this research requires the highest energies possible, particle physics research has been a major driver of new accelerator technology.

2 https://www.sckcen.be/en/Technology_future/A

STAR accelerator. Image courtesy ANSTO.

X-rays have long played a role in biological and medical research—James Watson, Francis Crick and Rosalind Franklin used X-ray diffraction to reveal the double helix of DNA. Today, synchrotron light allows scientists to look deep into the 3D structure of proteins while super-bright X-ray free-electron lasers (XFELs) are offering an unprecedented look inside molecular processes. The bottleneck in much of structural biology is the need to create a crystal of the biomolecule or protein that is required to be imaged. The new XFELs are so bright that it is anticipated they will see the structure of a single molecule. The pulses of light will be so short that it will be possible to watch chemical reactions take place, leading to the possibility of 'molecular movies'. This capability will transform much of science in the near future.

Synchrotron light allows the study of the structure of materials, on the scale of the separation of the atoms that the material is made of. It can provide information on the chemical and electronic structure, on microstructure and on the properties of surfaces, interfaces, thin films and multilayers. Synchrotron light can be used to create cross-sectional images of matter and to analyse dynamical processes on very short time scales. It is an indispensable tool for applied research in a great variety of areas, such as the development of new materials with relevance to nanotechnology, electronics and communications, energy generation and storage, medicine and health care, transport and the environment.

A recent development in heavy ion accelerators is new technology to create accelerated rare isotope beams (RIB), generated by starting with very high-power beams of stable isotopes. RIBs are beams of exotic short-lived atomic nuclei that are not found naturally on Earth, and which are now enabling the study of how the properties of the nucleus change with extreme changes in the ratio of neutrons to protons. Ultimately this will result in a full understanding of how elements heavier than hydrogen and helium form in stars, particularly during violent cosmic events such as supernovae, answering some of the most burning questions in nuclear astrophysics. With a better understanding of nuclear processes in the universe, elemental abundances can then act as more and more sensitive fingerprints revealing the history of the Universe. Billions of dollars are being invested in large facilities producing accelerated rare isotope beams in Japan, the US, Germany and China, among others. Australia recently developed a small, specialised RIB capability.

Another application of heavy ion accelerators is the relatively new field of accelerator mass spectrometry (AMS). This allows the measurement of extremely low concentrations of radioisotopes by counting their atoms one-by-one, rather than trying to measure their decay. This has led to a million-times increase in sensitivity. AMS has opened the way to high-efficiency measurement in natural materials of long-lived radioactive isotopes, which may be natural or man-made, and for which decay counting is impossible due to the long half-lives. It has revolutionised many fields because of the unprecedented sensitivity that can be achieved—equivalent to finding a grain of sugar in the Melbourne Cricket Ground stadium if it were filled to the brim with salt.

ANSTO researchers gather samples that will be analysed using AMS. Image courtesy ANSTO.

Using AMS to measure radiocarbon (carbon-14) is the most common example, but techniques have been developed for many other isotopes of elements spanning the periodic table, from beryllium-10 to isotopes of plutonium. There are now more than 100 laboratories worldwide engaged in AMS, many of which are dedicated facilities, and the number continues to grow each year. The US Department of Energy's review, *Accelerators for America's Future*, noted: 'The trend to more compact facilities has continued, although several larger accelerators remain at the forefront of AMS'[3]. The ANU and ANSTO accelerators in Australia are among these, with the ANU Heavy Ion Accelerator Facility providing the highest energy routine AMS capability in the world.

AMS is now used in a wide range of fields, for both dating and tracing purposes. These include studies of our atmosphere, of water resources and ocean circulation, of ancient climates through polar ice and lake sediment studies, of geological processes including landscape dating, and now of cosmic processes, such as nearby supernova explosions in the distant past. AMS is also used in nuclear safeguards and forensics, and in tracer studies in biological systems, including medical and pharmaceutical applications.

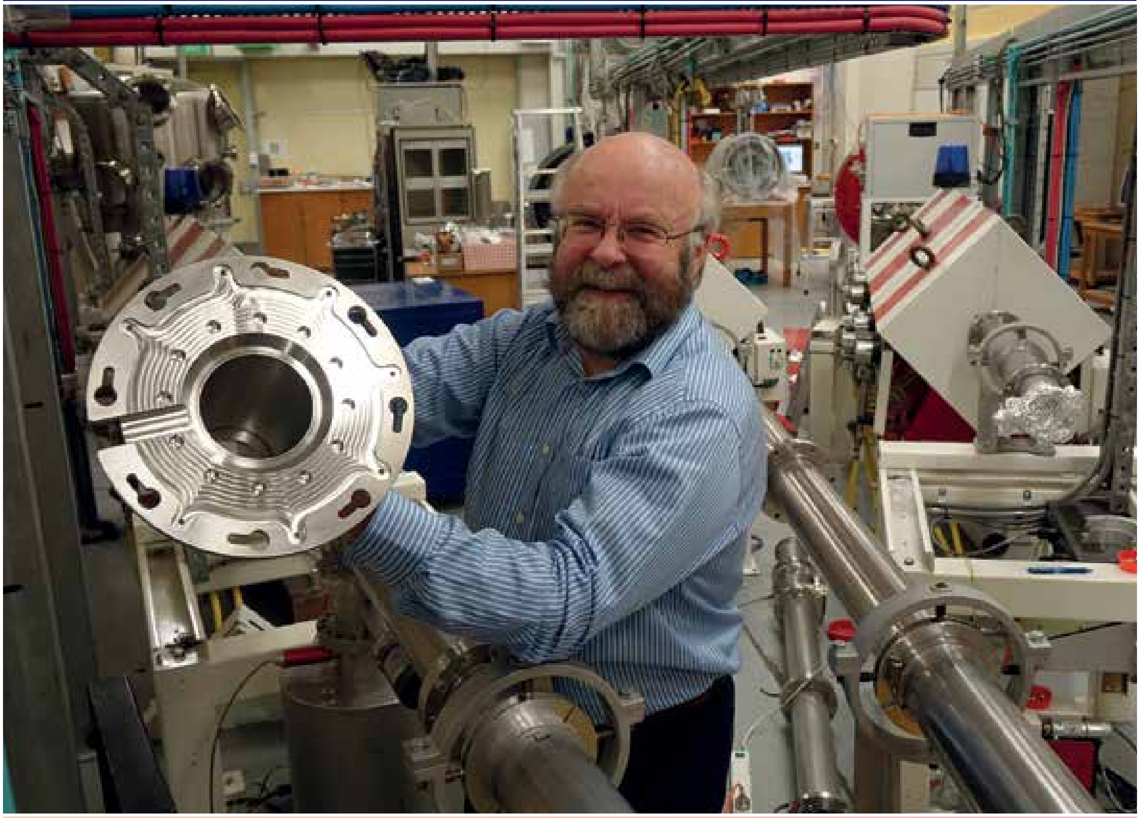
Materials science is a vast field that is highly dependent on accelerators of many types. Beams of photons, neutrons, heavy ions and muons enable the study of materials at the atomic level, which leads to greater understanding of the structure and nature of those materials, and enables the development of new materials, such as super-strong and lightweight 'designer' carbons, metal alloys, quantum dots and nanomaterials.

vii. Cultural application

Accelerators have also found a home in the arts. Ion beam analysis uses the ion beams from a particle accelerator to analyse materials, such as paint, without altering or destroying it, and without the need for the sample to be in a vacuum. Ion beam analysis has been used to study the components, such as inks, glass, ceramics and gems, in works of art and archaeological finds. The ultra-sensitive AMS technique is used for dating tiny samples of material, including seeds and fragments from archaeological sites.

3 *Accelerators for America's Future*, U.S. Department of Energy (2010) http://science.energy.gov/~/media/hep/pdf/accelerator-rd-stewardship/Report.pdf

New superheavy element 117



The heaviest element yet is set to make its debut on the periodic table, thanks to work by an international team of physicists and chemists, including researchers from the Australian National University's Heavy Ion Accelerator Facility, who were invited to join the collaboration.

Element 117 contains 117 protons, making it significantly heavier than the heaviest naturally-occurring element uranium, which has 92 protons.

By firing more than 10 billion billion rare calcium-48 nuclei at a target of the even rarer Berkelium-249 isotope, using the UNILAC linear accelerator at the GSI Helmholtz Centre for Heavy Ion Research in Darmstadt, Germany, researchers managed to create four atoms of element 117; enough to independently confirm work by researchers from Russia in 2010.

Superheavy elements like element 117 have not been found in nature, and are created artificially by nuclear fusion—combining the nuclei of two smaller atoms to create the bigger nucleus with the desired number of protons.

Speed and timing were of the essence in this research, as the Berkelium-249 isotope has a half-life of only 330 days. This material was created at the High Flux Isotope Reactor at Oak Ridge in the US, and then rushed to Germany to be made into a thin (0.0004 mm) target.

The creation of superheavy elements and exploration of their properties provides valuable data and opportunities for a wide range of scientific fields including quantum and nuclear physics, astrophysics and chemistry. However, the experiments to create them are extremely challenging. The probability that the two nuclei being smashed together will actually fuse is extremely low. Even if the two nuclei touch, they may stick together for only a hundredth of a billion billionth of a second. The longer they stick together, the greater the chance that an atom of the new superheavy element will be created.

The research team at the ANU Heavy Ion Accelerator Facility has developed a unique capability to measure how long the two nuclei stick together in these collisions—vital information to determine the best way to form the next superheavy elements, such as 119 and 120.

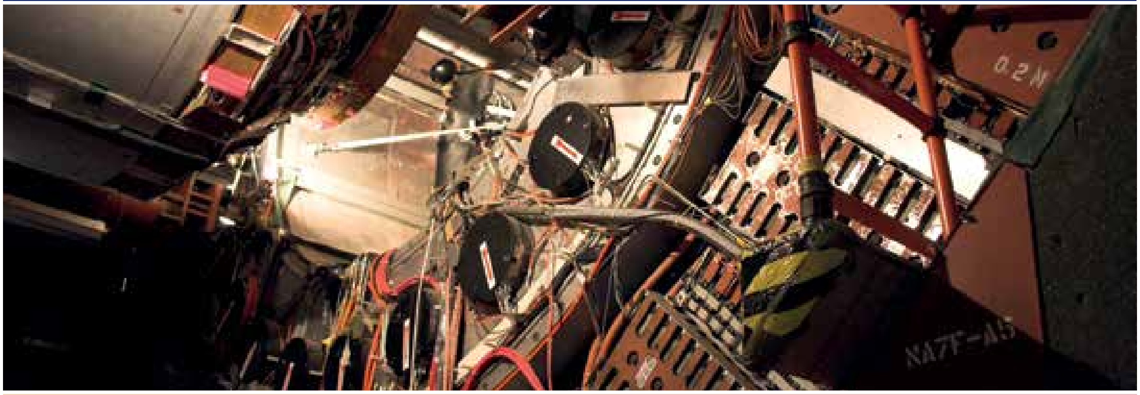
ABOVE: Demonstrating new equipment for the next stage experiments to investigate superheavy element formation reactions. Image courtesy D.J. Hinde, ANU.

1.3 The development of accelerator technology

Manufacturing accelerators has become big business. More than 65 companies and institutes build about 1000 new accelerator systems per year, generating annual revenues of more than US$3.5 billion, a figure growing at more than 10% annually. It is estimated that about US$500 billion worth of products are created or processed using accelerators every year[4].

With ongoing technical developments, accelerator costs are coming down and, if the benefits of scale can be realised, they will offer a cheaper approach to future applications as well as fundamental research. By one measure, the capability offered by accelerators is increasing at a rate that exceeds Moore's Law (wherein the processing power of computer hardware doubles approximately every two years). With the advent of new beam technologies, such as free-electron lasers—sometimes referred to as 4th generation light sources—the pace of development is set to increase even further.

FELs and XFELs



Free-electron lasers (FELs) are particle accelerators that achieve extremely high brightness and short duration photon pulses by passing high-energy electrons through a magnetic array called an undulator. Unlike storage ring light sources that deliver broadband synchrotron radiation, FELs deliver a very narrow range of photon wavelengths. The advantage this gives over conventional light sources is that it results in extremely bright light delivered in pulses as short as a femtosecond, or one-millionth of one-billionth of a second; the timescale on which chemical reactions take place. This will unlock new science on a scale that has not been seen before. FELs can produce light at X-ray wavelengths, and successive pulses from an X-ray free-electron laser (XFEL) can capture millions of frames to create an X-ray 'movie' of chemical, biological and atomic processes. This level of precision also requires complicated timing systems and feedback stabilisation of the accelerator systems, laser systems and X-ray detector systems.

XFELs have only recently been developed—the first was the US$379 million Linac Coherent Light Source (LCLS) at the SLAC National Accelerator Laboratory at Stanford University in the US in 2009—and more are either being planned or are under construction worldwide. These facilities offer X-rays that are several billion times brighter than previous instruments, and open up a whole new field of science, including the capacity to see inside single molecules. Demand for research time on these machines is high enough that the US is planning to upgrade the original LCLS to provide three times as much access to a beamline at any one time by 2018. Meanwhile, Japan began operating its SACLA XFEL in 2011, using a compact accelerator that is both brighter and more compact than SLAC's LCLS. By 2017, several European research institutions will begin operating an XFEL in Hamburg that will generate many thousands of pulses per second at the same brightness as SACLA. Switzerland's SwissFEL in Zurich is due to complete construction in 2016, and South Korea is constructing PAL-XFEL with the aim to complete the first phase and then expand capacity by 40% by 2018.

ABOVE: An inside view of SLAC's large detectors. Image courtesy Justin Lebar.

4 Hamm, Robert W, 'Industries thrive on particle beams', *Symmetry Magazine*, October 2009, Fermilab; and US Department of Energy. (2010) *Accelerators for America's future*, June 2010.

2 Accelerators in Australia

2.1 Facilities

Australia is equipped with a range of accelerator technology, ranging from several large national facilities, notably the Australian Synchrotron, to hundreds of smaller accelerators with applications in medicine, research and industry.

The jewel in the crown of Australian accelerators is the **Australian Synchrotron**. The Australian Science and Technology Council first proposed the need for synchrotron access in detail in the *Small Country—Big Science* report in 1990[5]. The Australian Synchrotron is a Melbourne-based high-energy electron synchrotron accelerator. It is essentially an intense source of light, from infrared to hard X-rays, many times brighter than the sun. The Australian Synchrotron first became operational in July 2007, with beamlines for experiments in areas such as imaging and medical therapy, infrared and soft X-ray spectroscopy, and protein crystallography. The demand for the facility continues to grow and has consistently exceeded capacity. There is an ongoing need for more investment to allow the Australian Synchrotron to respond to its growing user base, and for it to keep pace with global developments.

An aerial view of the Australian Synchrotron in Melbourne. Image courtesy Australian Synchrotron.

5 *Small Country—Big Science : A report to the Prime Minister on Australian Participation in Major International Accelerator and Beam Facilities*, by the Australian Science and Technology Council (ASTEC) (1990).

The ANTARES Tandem accelerator. Image courtesy ANSTO.

The **Australian Nuclear Science and Technology (ANSTO) Centre for Accelerator Science** at Lucas Heights in Sydney houses four instruments: the 10 million volt ANTARES tandem electrostatic accelerator (1991); the STAR Tandetron (2003); VEGA, a new low-energy multi-isotope mass spectrometry accelerator (2012); and SIRIUS, a medium-energy tandem accelerator (2014). All four are used for materials analysis and biological and environmental studies.

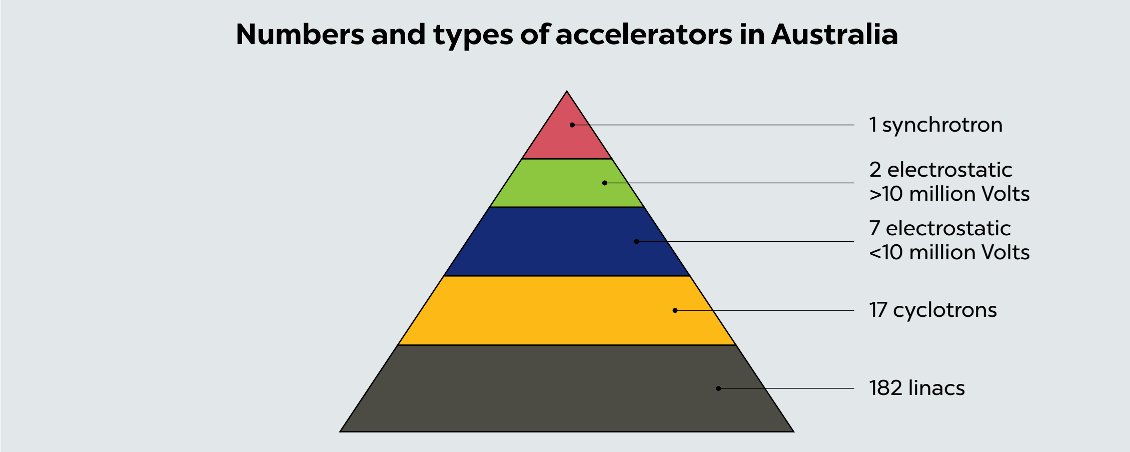
The **Australian National University's** Research School of Physics and Engineering operates two accelerator facilities. The first is the **Heavy Ion Accelerator Facility** (HIAF) in the Department of Nuclear Physics. This consists of a 15 million volt electrostatic tandem accelerator coupled to a superconducting linear booster accelerator. The tandem accelerator is among the five highest voltage electrostatic accelerators operating in the world. It is mainly used for fundamental nuclear physics research and for the development and applications of accelerator mass spectrometry (AMS) techniques, for which it achieves world-record sensitivity (capable of isolating one atom of a radioactive isotope among 100 million billion stable atoms). The second facility comprises a suite of smaller heavy ion accelerators operated by the **Department of Electronic Materials Engineering**, optimised for ion beam analysis and materials modification by ion implantation.

The Australian National University's Heavy Ion Accelerator Facility tower in Canberra. Image courtesy D.J. Hinde.

The Experimental Condensed Matter Physics group at The **University of Melbourne** operates a five million volt electrostatic accelerator, supporting two nuclear microprobe beamlines. The group also operates a low-energy Colutron ion implanter and has close links with CSIRO and quantum computing research.

Dr Jessica van Donkelaar and Dr Melvin Jakob, members of CQC2T, with the Colutron system. Image courtesy Grant Turner, MediaKoo.

The Australian Synchrotron and ANSTO accelerators are user facilities operated by staff scientists. Visiting scientists using the equipment require no prior accelerator knowledge to conduct their studies. In contrast, the university-based heavy-ion accelerators are generally operated by the scientists who are using the accelerator to carrying out their research. This extends to undergraduate and postgraduate students engaging in research projects, and learning the principles behind the generation of the accelerated beam is part of their training program. At all facilities, the accelerators are maintained by highly experienced technical and engineering accelerator staff, some of whom also conduct research in accelerator technology to improve and enhance their accelerators' performance.



Much more common than these large accelerator facilities are the cyclotrons used for medical, industrial and research needs. Medical cyclotrons and linear accelerators are operated at more than a dozen locations around Australia, in hospitals, government agencies and private companies. The bulk of accelerators, outnumbering all other types, are the electron linear accelerators, used for cancer therapy on a daily basis.

2.2 How are accelerators used in Australia?

Applications of accelerator technology in Australia can be found in airports in the form of X-ray imagers; they are found in plastics used to wrap perishable products, where charged particle beams are used to induce polymerisation in target materials; and they are found in hospitals, medical facilities and dental clinics around the country. Applications can also be found in the very food we eat, where accelerator technology is used to produce the high-energy radiation used to increase the useful life of food. They also make significant contributions in unexpected areas, such as in environmental applications, where Australia is a world leader in AMS dating and tracing techniques.

The breadth of the application of accelerators encourages collaboration across scientific and technical disciplines. This convergence of approaches is part of promising developments addressing many currently intractable or difficult problems—especially those involving many variables such as climate and environmental science, and energy systems.

i. Environment

The technique of AMS has many applications in the environmental field. AMS measures the concentrations of vanishingly rare radioactive isotopes. This is achieved by an extraordinarily sensitive accelerator-based technique to identify and count the undecayed atoms of the isotopes in the sample. This contrasts with measuring the radiation emitted when the radioactive nuclei decay. With half-lives up to millions of years, decay counting has obvious limitations—the human lifetime being one! Even for the well-known carbon-14 dating, where the half-life is only 5715 years, the AMS technique represents a great improvement. The sample size required to measure a date by AMS is a factor of 1000 smaller, measurement times are much shorter and throughput much higher. This allows researchers to address fundamentally different questions requiring large data sets, obtaining dates from small samples such as individual seeds, pollen, small bones and small pieces of charcoal. Radiocarbon is also widely used as a tracer to investigate movement of materials in the environment. This exploits the doubling of the radiocarbon concentration in the atmosphere during the nuclear testing era. Applications of this range widely, from oceanography to understanding the global carbon cycle. Active research in most of these areas is going on in Australia.

As well as carbon-14, other longer-lived radioisotopes are produced by cosmic ray bombardment of the Earth. The isotope chlorine-36 is produced in the atmosphere by cosmic rays, and falls out in rainfall along with stable isotopes of chlorine that are derived from sea spray. Its concentration can show how long water has been underground, and trace groundwater flow and mixing between aquifers. The ANU and shortly the ANSTO AMS facilities are among only a handful in the world that can measure this isotope routinely

Sustainable water supplies

Water is a particularly valuable commodity for residents of Western Australia's remote and arid Pilbara region. Groundwater supplies exist but it was not known how sustainable a resource these might be in the long term.

The challenge for ANSTO's seven-year Isotopes for Water project was to investigate the groundwater quality, age, and sustainability, to work out if these supplies would be enough to support continued population growth in the area. Using ANSTO's STAR accelerator, researchers analysed the minute traces of radiocarbon (carbon-14) in the groundwater, from which they were able to determine the age of the water. They could then calculate the rate at which the groundwater supplies recharge and therefore the rate at which water can be extracted sustainably. They showed that the groundwater supplies were mostly around 5000 years old, but in one particular area, the groundwater was 40 000 years old. While the 5000-year-old water is recharged sufficiently from cyclones, the 40 000-year-old vintage region will not recharge fast enough to be used as a water source.

at the required sensitivity. Cosmic rays also bombard the rocks at the Earth's surface. The build-up of radioisotopes can reveal the time since the rock was first exposed at the surface. Alternatively, if the rock has been exposed for a long time, the concentration indicates the rate at which it is eroding.

AMS measurements of concentrations of man-made radioactive isotopes of heavy elements, such as uranium and plutonium, are also being pioneered in Australia to probe ore bodies, trace discharges and to investigate soil erosion—a vital topic in Australia. Isotopes of plutonium were produced and distributed globally by atmospheric nuclear tests, principally between 1954 and 1962. After falling out in rainfall, plutonium binds strongly to soil grains. Subsequent loss of soil then depletes the inventory of plutonium, and a measurement thus allows the loss to be quantified. Concentrations are extraordinarily low, and accelerator mass spectrometry is by far the most sensitive technique for measuring them.

Both ANSTO and ANU operate accelerators that can make ultra-sensitive AMS measurements. At ANSTO there are now four accelerators committed fully or partially to AMS. These range in voltage from 1–10 million volts, and allow a broad range of applications and method development. The 15 million volt electrostatic accelerator at the ANU is the highest energy accelerator in the world used for routine AMS measurements. Its size and flexibility—and the fact that it's in a nuclear physics laboratory—have allowed ANU researchers to develop new methods and applications, gaining an international reputation as one of the most innovative AMS labs worldwide. Both institutions serve a wide community of researchers from university and government research organisations and industry, and both are major players on the world stage. Demand for AMS measurements—

Accelerator Mass Spectrometry and Manganese-53

Australian researchers from the ANU Heavy Ion Accelerator Facility and ANSTO are pioneering new techniques in accelerator mass spectrometry that will allow the dating of ancient geological features more than 10 million years old.

Instead of looking for the decay of radioactive isotopes, the technique—single atom counting—identifies and counts the radioactive atoms themselves, using techniques derived from nuclear physics. Using this approach, researchers are able to measure concentrations of manganese-53 (^{53}Mn); a rare isotope that is produced when cosmic rays collide with iron atoms in rocks on the Earth's surface. ^{53}Mn has a half-life of around four million years, which makes it impossible to measure using the decay counting method. Using the 15 million-volt electrostatic accelerator at the ANU and a specialised mass separator and ion detector, the team can separate and directly count each atom of ^{53}Mn in a rock sample, down to concentrations of one atom of ^{53}Mn in 100 million million atoms of iron.

This is particularly useful in Australia's iron-rich landscapes. The technique will help provide data on soil erosion, the formation of desert features, the development of glaciers and the effects of rainfall changes, all of which are valuable for testing our understanding of climate models.

Karina Meredith from ANSTO's Isotopes for Water project collects samples of groundwater in Western Australia. ANSTO's Institute of Environmental Research is a centre of research excellence conducting studies to understand how environmental systems function and interact, and the impact that humans are having on the environment. Image courtesy ANSTO.

Analysing air pollution

Australia's heavy ion accelerators are being used to analyse air pollution in cities such as Manila in the Philippines.

For more than a decade, Professor David Cohen of ANSTO has used the same accelerators to track down the sources of fine particle air pollution in Australian and Asian cities. Air pollution particles come in different sizes, but fine particles are the most damaging to human health—they penetrate deep into the lungs and have been linked to cardiovascular disease.

Professor Cohen is the data coordinator of an international study of fine particle air pollution that takes samples in cities across 15 countries in Asia and Australasia. Combining the fingerprints detected using the STAR accelerator with wind back-trajectories, he has shown that the air in Hanoi, for example, can contain dust from the Gobi Desert in Mongolia and pollution from Chinese coal-fired power stations some 500–1500 km away.

In addition, to reveal the sources of air pollution nationally, Professor Cohen's team has recently completed a study of the Upper Hunter region of NSW. This found that in winter, up to 80% of the fine particles in the area were coming from domestic wood burning. This suggested that one of the most effective ways to reduce winter air pollution is to regulate wood burning.

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from within Australia and overseas—is high, and the two facilities are complementary.

In the environmental field, ion beam analysis is used as well as the AMS technique. For example, ANSTO uses accelerated ion beams to analyse fine-particle pollution, generated by industry, coal-fired power stations, trucks, cars and other man-made sources. These particles are too small to see—less than 2.5 micrometres, or 30 times smaller than the width of a human hair. At high concentrations they can cause significant health problems, penetrating deep into the lungs and bloodstream.

ANSTO's STAR and ANTARES accelerators are also used for ion beam analysis to determine the presence and quantity of heavy metals in fish, cattle and wildlife, and to study archaeological rock and soil specimens.

Ion implantation at ANSTO has also been used to research applications for 'sol-gel', a method for creating solid materials from small nanoparticles dispersed in a liquid. This led to the development of a nanoparticulate membrane bioreactor that can treat wastewater 10–15 times faster than conventional techniques. The sol-gel technology was commercialised in 2012 by Australian clean-tech company BioGill, which now makes systems sold internationally for treating wastewater from breweries, wineries, food manufacturing and detergent plants, and hopes to float on the stock exchange in five years.

Access to ANSTO accelerators within Australasia is facilitated by the Australian Institute of Nuclear Science and Engineering (AINSE), whose membership includes 42 Australian and New Zealand universities. ANSTO also has research partnerships with 36 international research organisations.

ii. Medicine

Diagnosis and treatment through radiation (nuclear medicine, radiology and radiation oncology) have changed the course of health care and touched all our lives. From imaging through X-rays and PET, to targeting cancers by introducing radioactive isotopes into the body (brachytherapy), accelerators play a central role in healthcare in Australia, and this role is set to grow.

Australia's medical cyclotrons produce proton beams that are used to manufacture radioisotopes used in medical diagnosis, principally for PET and SPECT. Accelerator-produced radioisotopes are also important for treatment, for example, actinium-225 is used for alpha particle mediated radio-immunotherapy. Radiochemistry is also an important downstream area of research that finds new delivery systems to optimise dose or improve specificity of the radioactive delivery system to the target ailment (thus improving targeting).

More than 50% of all new cancer patients will require radiotherapy, and X-rays are used to treat most cancers within the body. Generally, the X-rays are produced by an electron linear accelerator that provides effective and non-invasive treatment. While there are significant initial capital costs to set up a radiation oncology centre, radiation therapy is one of the cheapest and most cost effective cancer therapies available. In most cases, it is delivered as an outpatient treatment, further reducing costs. Sophisticated X-ray treatment regimens have been developed over the years, in particular an X-ray therapy known as intensity modulated radiation therapy (IMRT) and intensity modulated arc therapy (IMAT). These use special radiation beam-shaping devices called multileaf collimators, consisting of tens of motorised tungsten leaves moving in and out of the radiation field. Multileaf collimators can be stationary or move during treatment, allowing radiation intensity to change during a treatment session. This dose modulation results in more conformal dose distribution around the tumour target volume, while irradiating a lesser volume of surrounding healthy tissues. This promises better treatment outcomes than conventional treatment.

True Beam medical linear accelerator used for radiation treatment of cancer patients. Image courtesy Varian Medical Systems. Copyright ©2007, Varian Medical Systems, Inc.

Australia needs to plan for an increasing cancer incidence by expanding radiation oncology services. According to a survey conducted in 2012, as of December 2011 there were 168 medical linear accelerators installed across radiation oncology centres in Australia; 108 (64%) were in the public sector and 60 (36%) in the private sector[6]. By 2022, it is estimated that Australia will need 100 more, in addition to replacing the current inventory[7,10].

Even the Australian Synchrotron, the country's biggest accelerator, is being used in pre-clinical imaging, providing a unique ability to image whole animals while alive and with soft tissue contrast, as well as investigating novel radiotherapy methods.

Synchrotron radiation sources can provide photon beams of such finely tuneable energy and brightness that they can yield information on a wide range of materials for which traditional spectroscopic methods fail, such as live and wet biological tissue samples. They have become an indispensable tool in molecular biology, especially for understanding protein structures.

6 *Planning for the best: Tripartite national strategic plan for radiation oncology*, Royal Australian and New Zealand College of Radiologists (2012).

7 Projecting the radiation oncology workforce. Input to the Tripartite National Strategic Plan For Radiation Oncology in Australia. Report to The Royal Australian and New Zealand College of Radiologists, The Allen Consulting Group (2012); Delaney GP., Jacob S., Featherstone C., Barton MB. Radiotherapy in cancer care: estimating optimal utilisation from a review of evidence-based clinical guidelines. Collaboration for Cancer Outcomes Research and Evaluation (CCORE), Liverpool Hospital, Sydney, Australia, 2003 http://canceraustralia.gov.au/sites/default/files/publications/radiotherapyreport1_504af01e8daf0.pdf

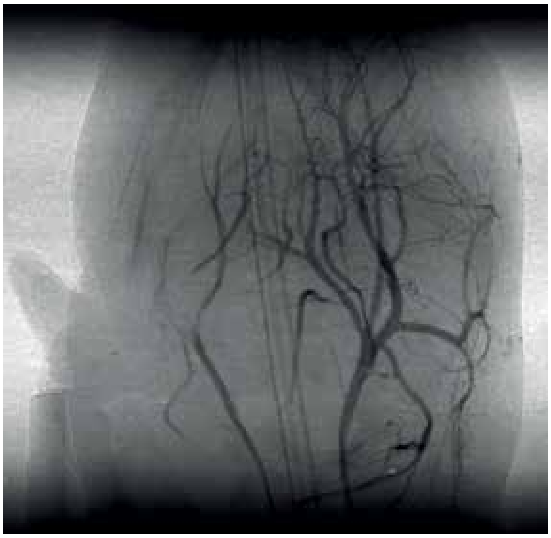


Image of brain vasculature in a rabbit demonstrating high-resolution and high-contrast using the same set-up available for whole animal imaging. Image courtesy James Pearson (Australian Synchrotron and Monash University).

Thanks to the use of synchrotron radiation, the vast majority of molecular structures are now understood rapidly and efficiently on crystallography beamlines. At the Australian Synchrotron, recent discoveries include how insulin binds to its receptor, understanding the role and function of certain types of immune system T-cells in the prevention of disease, and solving a century-old riddle about how blood clots form. Application of crystallography has also had significant commercial impact with Australian start-up companies involved in drug-discovery programs.

Researchers from the Walter and Eliza Hall Institute of Medical Research have used the synchrotron's crystallography functions to probe the structures of protein molecules involved in chronic lymphocytic leukaemia (CLL), a disease that affects around 1300 Australians each year. Their work in collaboration with two major pharmaceutical companies has led to a drug that represents a major advance for patients with this type of cancer. According to the institute: "Early-stage clinical trials suggest that the drug may lead to complete remission in one-quarter of patients with advanced CLL that isn't responding to other therapies[8].

From 'micro' to 'macro'

The flagship beamline of the Australian Synchrotron is the Imaging and Medical Beamline—the widest synchrotron light beam in the world. This size means it can be used to image tiny structures inside live organisms in real-time; a dynamic, three-dimensional X-ray imaging process. This translation of the microscopic to the macroscopic is a boon for researchers wanting to explore the immediate effects of a treatment approach on the physiological target, such as a particular organ, and on the entire biological system. For example, it is being used to explore how different treatments for cystic fibrosis affect the soft tissues of the airways and lungs.

Source: *KnowHow* magazine Issue 5. www.sciencemeetsbusiness.com.au. Reproduced with permission.

iii. Industry

Some examples of advanced materials applications by Australian researchers using accelerators include the development of novel hydride materials that can store high densities of hydrogen at low pressure, which is safer and less costly than compressed gas systems. This research has led to the formation of the company Hydrexia, which has raised $9.25 million in venture capital to commercialise the technology[9].

Another example is the discovery of a new 'trapdoor' technique that can reduce the cost of natural gas purification. Developed by a Melbourne team led by the Cooperative Research Centre for Greenhouse Gas Technologies, it also holds the promise of being used to cheaply capture and store carbon dioxide[10]. Both advances were made using the Australian Synchrotron.

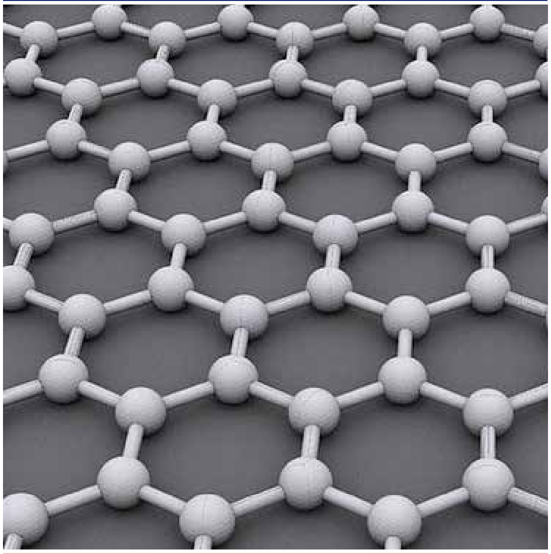
Devices such as focused ion beam milling machines are fast becoming a staple of the micro- and nano-fabrication world, and ion-beam implantation is also used to modify the electrical properties of materials with high precision.

8 Australian Synchotron (2014), Annual Report (i), 2014.

9 UniQuest, University of Queensland. (2013) *Hydrexia commercialisation story: Storage technology transforms the potential of hydrogen*. http://www.uniquest.com.au/filething/get/8613/Hydrexia%20Commercialisation%20Story.pdf

10 Jin Shang, et al. 2012, 'Discriminative separation of gases by a "molecular trapdoor" mechanism in chabazite zeolites', *Journal of the American Chemical Society*, 134: 19246–19253.

Synthesising functional materials



Graphene is a two-dimensional crystalline form of carbon with unique physical and chemical properties, including extremely high electrical and thermal conductivities. It has great potential for the fabrication of novel electronic and optoelectronic devices and is the focus of intense research effort.

Graphene can be produced using a range of synthesis techniques, including exfoliation of graphite, chemical synthesis, decomposition of silicon carbide surfaces and crystalline deposition on metal surfaces. For many applications it must then be transferred to a different substrate and/or patterned to form useful device structures. However, this is inefficient and time consuming, so there is great interest in developing new synthesis techniques.

Australian researchers have been working with international collaborators on two ion-implantation-based approaches to graphene synthesis. The first involves the precipitation and growth of graphene on carbon-implanted copper foils, while the second uses ion-irradiated silicon carbide to enhance graphene synthesis during laser annealing. In both cases, graphene only forms in the ion-irradiated areas, providing a convenient means of patterning.

Image courtesy AlexanderAIUS/wiki.

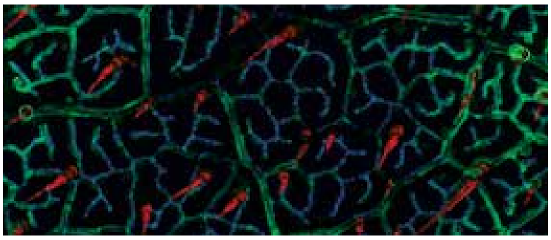
iv. Energy

The development of next-generation photovoltaic systems brings together physics, chemistry, electrical engineering, nanofabrication, environment and energy—and all of these rely on accelerators to make advances in the field. Australian researchers have a strong track record in this area and have used accelerator tools to further develop novel polymer-based photovoltaics which offer improved efficiency, flexibility and cost.

v. Fundamental research

Synchrotron science makes contributions across the full spectrum of research. It plays a particularly strong role in fundamental biological and chemical sciences. It helps us understand magnetic materials, complex surfaces and solid-state chemistry at a very deep level. Synchrotron methods provide insight into archaeology, palaeontology and environmental studies.

Details of the teeth in a fossil fish from the Gogo Formation are helping the study of some of the earliest vertebrates with jaws. Image courtesy Kate Trinajstic (Curtin University), Vincent Dupret (Australian National University) and Anton Maksimenko (Australian Synchrotron).



High resolution image of a leaf helping research into soil studies and metal toxicity and tolerance in plants (1 micron resolution, Red = phosphorus, Green = zinc, Blue = copper). Image courtesy Peter Kopittke (University of Queensland).

Synchrotron facilities serve as a meeting place for researchers from all fields, representing universities, government laboratories and industry.

Nuclear physics has been, and remains, a unique testing ground for quantum mechanics, the theoretical framework behind many modern technologies. Recent advances in quantum mechanics have shed light on the nature of the transition from generally small isolated systems described well by quantum mechanics, to larger systems whose behaviour can be described by the classical laws of physics. This transition is of general importance given the widespread trend for new technologies to move to smaller and smaller scales.

Australian researchers are pioneering experimental investigations to understand this transition in nuclear collisions, where Australia leads the world—as it does in key aspects of nuclear fusion, nuclear fission, and understanding the creation and structure of new heavy elements and isotopes. This position has only been possible because in the past Australia invested in one of the highest voltage electrostatic accelerators in the world, operating at up to 15 million volts, and developed a unique suite of ambitious detector systems, well matched to the strengths of the accelerator. This capability attracts international users from some of the world's biggest nuclear physics accelerator facilities in the US and Europe, as well as from South America and Asia. Australian researchers in turn obtain early and free access to these large overseas facilities. This is a concrete example of how well-planned Australian investment in our own research infrastructure can give tangible long-term returns.

Innovations exploiting the internal electronic structure of materials are at the foundation of many modern technologies, from microelectronics in IT to photovoltaic systems. New quantum technologies will emerge from this area in the future. Accelerators have played an essential role by accelerating ions that are implanted into semiconductor crystals to create transistors and other devices. The broadening of the contributions of accelerators and related know-how to explore future quantum technologies will have a big impact on everyday life. In the emerging field of quantum technologies these accelerator techniques are being extended, at the University of Melbourne and elsewhere in Australia, to configure devices that exploit the strange rules of quantum mechanics for useful applications. In the near future, Australian researchers will join their expertise in accelerated single ions with that in nanotechnology to develop new devices that store information in the quantum states of single implanted ions. The development of a practical method to create a large-scale quantum computer is one long-term goal of this research.

vi. Improvements in accelerator science and engineering

Given the impact and breadth of accelerator science applications, it is not surprising that research into accelerator technology itself is a fruitful area. Improvements in the quality, reliability and cost of accelerator systems can have a huge impact on downstream research and applications. Australia is fortunate in having several groups at universities and major research institutions that have deep technical capabilities and are working together through the Australian Collaboration for Accelerator Science.

Research and application of accelerator science and technology in Australia is broad, plentiful and of high quality. Accelerator-based research findings are published in influential international journals. In the case of research into nuclear fusion, heavy ion accelerator-based research carried out in Australia has changed the direction of research in the field worldwide. Accelerators also produce applications with valuable economic and health impacts.

Accelerator research and development is currently active on many fronts and presents a range of exciting opportunities for Australian researchers. Local accelerator facilities need to be developed to stay at the leading edge in their research fields. Future research accelerators in some areas, particularly particle physics, will require a global effort to realise ambitious design goals. Australia is showing strong results from research into low-emittance electron storage rings, critical achievements required for future synchrotron light sources and damping rings for high luminosity linear colliders for high-energy physics.

Australia is both a major beneficiary of accelerators and, to a lesser extent, a contributor to the development of accelerator technologies.

As a nation, we must continue to develop our technological base. We need to provide continuing support to our own world-class accelerators and their national and international users, thus making the strongest impact in international science. This will ensure that we in turn continue to have access to the world's largest instruments and facilities—allowing us to reap the health and economic benefits offered by large-scale international accelerator developments.

Most accelerators are large-scale, long-term investments, both in hardware and accelerator personnel. We need to recognise that long-term support is required for accelerator-based programs and facilities—both within Australia and through international partnerships—to ensure that their benefits are fully realised, and that we continue to play a globally-significant role.

2.3 Maintaining and improving accelerator capabilities

National accelerator facilities form an important component in the spectrum of scientific infrastructure in any country. With well-conceived integration of accelerator and instrumentation, they can provide easy access to a range of capabilities necessary to carry out frontier research, for both local users and international collaborators. Importantly, they also provide for the growth of national expertise. Such facilities can act as a crucible for both expertise and technology development to feed the next generation of accelerator infrastructure.

Through technology transfer agreements, local industries can become high-technology suppliers to local and international projects. Through the development of prototype experimental facilities in collaboration with research scientists and engineers, production equipment supply can become a springboard to related products and services domestically and overseas.

Australia has already embarked on a national program of operation of a major accelerator facility with the Australian Synchrotron. Facilities of such scale and impact are not entered into lightly, and must have a program of development and improvement with a decade timescale, in addition to operation and maintenance to provide efficient and optimised exploitation. Such a facility is neither 'turn-key' nor immutable in operation. It provides high-quality national infrastructure that can—and, for maximising return on investment, must—be continually improved, making use of local and international expertise and innovation.

To have a realistic chance of achieving such continuous improvement and innovation, it is essential to have a professional workforce of the highest capability, and expertise in the fundamentals as well as the technology underlying such facilities. The provision of such a rich source of skills and knowledge naturally includes bringing international experts to Australia on a short- and long-term basis, but importantly leads inevitably to the need to develop a strong local workforce trained at the cutting edge of accelerator science.

While the various leading accelerator laboratories worldwide provide a rich resource of expertise that we must exploit, the best source of local innovation is through a significant program of high-level research into accelerators involving PhD degree programs within Australian research universities.

National facilities like the Australian Synchrotron need a strong base of expertise for future development and collaboration. Not just a good team of technicians, physicists, engineers, chemists, biologists and other experts to keep research results flowing, but also a group of very sharp, well-educated and trained accelerator specialists capable of innovation, international collaboration and advances of significance. To achieve all this, Australia needs a high-level R&D program that attracts the best students. There is a need for Australian universities to develop an outstanding program in accelerator R&D, collaborating in international projects at the very cutting edge of innovation in high-performance accelerators—those with high energy, high intensity or high power. Such a base of frontier accelerator R&D would feed through to a self-supporting structure of accelerator scientists for the broader Australian community.

The accelerator ecosystem and national skills development

To understand the fundamentals of the technology is to be able to further develop it, to develop major alternatives and to apply it in opportune ways. Having strong local expertise in understanding, developing and enhancing core accelerator infrastructure and technology can encourage the expansion of skills and industrial supply capabilities in a range of key and ancillary products and services. These can include magnets (e.g. MRI scanners, electric motors, generators), radio-frequency engineering (e.g. RF oscillators, transmission lines, modulators), large-scale vacuum systems (e.g. vacuum engineering in metal alloy manufacture, porosity sealing in metals and polymers), electronic control and monitoring systems, complex design tools, and high-performance computation data handling and modelling.

Furthermore, accelerator-based technology finds a broad range of applications, for example in radiotherapy (proton and heavy ion beam systems), medical imaging systems, high-power and high-precision magnet systems (both room temperature and superconducting), and in industrial applications. A strong engagement with frontier facilities results in expertise that feeds new advances and developments back into real-world applications.

The country's largest accelerator facility, the Australian Synchrotron, hosts more than 4000 researchers and operates more than 900 experiments from across Australian industry and academia each year. This develops core expertise that enhances the national skills base in new technologies that are used widely in cutting-edge manufacturing and engineering.

3 Australia’s research in a global context

3.1 The globalisation of science

Major research facilities around the world are increasingly dependent on collaboration for the sharing of resources and capabilities not available (or possible) at the institute level, and often not available in their own countries. This growing tendency for large, shared facilities and multiple international collaborations is inexorable, and is happening for a number of reasons:

» research is now addressing global problems

» with increasing numbers of countries engaging in scientific research, expertise, resources and information are spread much more widely than a century ago

» the costs of the research infrastructure needed to make advances in the sciences are such that no single nation can build and maintain all the infrastructure it needs to maintain high-level capability across the breadth and depth of research disciplines

» the clear benefits of collaboration—in impact, efficiency, knowledge-sharing and capacity building—multiplies the return on investment by any institute, university or nation.

The Department of Industry (2011) succinctly described the Australian context for international collaboration:

> *“The relative costs of collaboration have reduced as a result of the increasing mobility of scientists and the widespread use of modern ICT, allowing researchers to exchange information and organise global research networks. International collaboration, however, is not without its costs and challenges. People, organisations and countries must balance the benefits of collaboration with the loss of some control, added administrative complexity, the need to modify or adjust national priorities, funding plans and schedules, and the potential difficulties of staff working abroad.”*[11]

It is imperative for smaller economies such as Australia to embrace this development and fully participate, both in the use of such facilities and in the development of the technology and expertise required for the facilities themselves.

Conversely, in areas where Australia has expertise and facilities that attract international users, these facilities and their international users need continuing support so that Australia can make its own unique contribution in the globalisation of science.

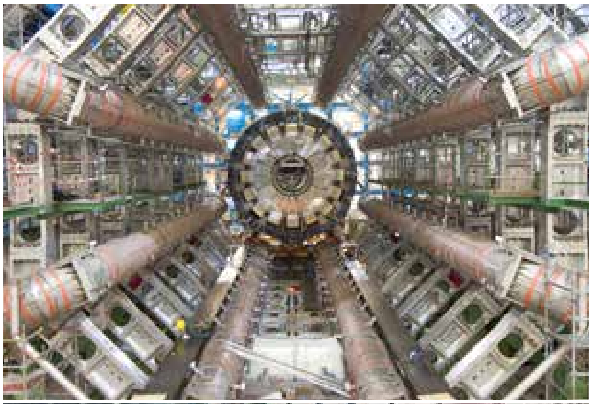
Countries like Australia can benefit from opportunities to collaborate in large international facilities that would otherwise be out of reach. Major international accelerator-based facilities include high-energy colliders; high-intensity light sources; high-power proton beams for supplying high-intensity neutrons, neutrinos and other secondary particle beams; radioactive ion beams; and potentially, beam-controlled fusion systems. Australia must develop a major program of accelerator R&D to allow it to fully partner in facilities, such as the Large Hadron Collider (LHC), the proposed US$10 billion International Linear Collider (ILC), coherent X-ray sources such as the Linac Coherent Light Source (LCLS), major projects being planned in China, and various other high-power proton sources.

Australian science provides a steady flow of advice to international facilities such as these, for example via advisory committees, and helps solve technological problems through the provision of expert advice. We also draw on the international community to help with our own research and development, input that is valuable in advancing our national research priorities.

11 *Science and research collaboration between Australia and China*, Department of Industry, Innovation, Science, Research and Tertiary Education (2011)

Detecting the Higgs Boson

One of the world's largest international collaborations, and one in which Australia has played a significant role, is the ATLAS experiment at CERN. It consists of more than 3000 scientists (including 1000 graduate students) from 38 countries and 174 universities and research institutes. The ATLAS particle detector instrument itself is 46m long and 25m wide, houses 3000km of cabling and weighs 7000 tonnes—equivalent to 40 Boeing 747 jets. It collects 3200 terabytes of data each year, equivalent to three billion books. To confirm the existence of the Higgs boson in 2012, the instrument had to carefully measure 10^{13} (or 10 000 billion) particle interactions.



ABOVE RIGHT: Installing the ATLAS calorimeter.
Image courtesy ATLAS Experiment © 2014 CERN

RIGHT: ATLAS collaborators.
Image courtesy ATLAS Experiment © 2014 CERN

3.2 Access to accelerators overseas

Researchers from a range of scientific disciplines, industry and medicine rely on access to synchrotron light sources, high-energy particle accelerators, rare isotope heavy ion accelerators and neutron sources at overseas accelerator laboratories. Australian researchers have access to the world's biggest and best-performing accelerators overseas and offer international researchers collaborative access to Australian accelerator-based facilities with complementary capabilities. Australian researchers also contribute their skills and intellect via collaborative research programs between local and international institutions. To continue developing the research tools that support further scientific discoveries, Australian scientists need continued access to world-class accelerator infrastructure.

The biggest example of this is the Australian high-energy physics community's use of the Large Hadron Collider at CERN. Australian researchers made substantial contributions to the 7000-tonne ATLAS particle detector used to confirm the Higgs boson particle in 2012, discovery of which led directly to the 2013 Nobel Prize in Physics.

ATLAS is designed to probe phenomena that will likely shed light on new directions for particle physics theories beyond the Standard Model, the most successful current model, which is, however, known to be incomplete. Both ATLAS and the Large Hadron Collider will continue operating to 2022, when an upgrade is planned to allow the accelerator to explore even higher energies and probe even more deeply into the underlying structure of matter.

Another example comes from nuclear physics, with Australian researchers being granted early access to new international-scale rare isotope beam facilities. This has come about because scientists from those facilities have been attracted to collaborate with Australian researchers, and have travelled to Australia to carry out complementary measurements at Australia's nuclear physics accelerator at the ANU Heavy Ion Accelerator Facility.

An organisation helping to facilitate these links is the Australian Collaboration for Accelerator Science, which was founded in 2010 as a joint venture between the Australian Synchrotron, ANSTO, the Australian National University and the University of Melbourne. Despite having no formal funding mechanism, it helps facilitate international collaborations that, besides each collaboration's inherent research value, provides Australian researchers access to the best facilities around the world. ACAS works with government, university and industry partners to provide a framework for Australian scientists, engineers and experts to conduct accelerator research and training locally and overseas.

Spring-8 Angstrom Compact Free Electron Laser (SACLA) at the RIKEN Harima Institute, Japan. Image courtesy RIKEN.

Elettra Sincrotrone Trieste (Italy), a European research facility housing two advanced light sources, the electron storage ring Elettra and the free-electron laser (FEL) FERMI. The centre also houses the European Storage Ring FEL Project (EUFELE). Photo by Gabriele Crozzoli, courtesy Elettra Sincrotrone Trieste.

Through organising training schools, it also aims to "nurture and inspire the next generation of scientists to work in the field of accelerator science and design the accelerators of the future."[12]

3.3 International partnerships: A two-way street

A two-way flow of scientific and technical personnel arises not just from operating accelerator facilities, but also through having an active community of accelerator developers, thus attracting international experts to Australia. Without local facilities and research programs of very high quality, no incentives will exist for international research bodies—and leading international innovators—to seek partnerships with Australian researchers in fundamental and applied research efforts. Without these incentives for research partnerships, Australia will be seen as a customer for accelerator-related products and services rather than a provider and co-developer. It will be a technology follower, not a technology leader.

i. Exploiting opportunities in global large-scale manufacture

To date, Australia has missed out on the large industrial and manufacturing contracts—in Australia, the Asia–Pacific region and further afield—for the most capital-intensive part of accelerator facilities: building the accelerators themselves. For example, in the construction of the Large Hadron Collider facility at CERN, which cost about US$4 billion, the biggest part of the cost was for its numerous dipole magnets. Contracts for these were awarded to companies partnering in their R&D, and construction was highly geared towards industrial production. Australian industry was not capable of contributing to the accelerator construction itself. Australian researchers did play an important role in the development and construction of the US$600 million ATLAS detector system, which was mostly custom-designed and built, with much of the component assembly carried out within collaborating research institutes.

Another example is the $221 million Australian Synchrotron: it was designed by an international team of accelerator experts, which was followed by an international tender for all its major components. Only infrastructure such as buildings and construction could be supplied locally.

While participation in construction of the Australian Synchrotron and the Large Hadron Collider could be seen as two examples of missed opportunities, there are several other large projects internationally, both planned and under way, where significant innovation will be required to achieve a range of goals, and Australian researchers and industry can play a part. Accelerator development and construction is not static, since the demands for higher performance demand innovation, and Australian expertise is both sought after and available.

Current technology, such as the superconducting magnets and RF cavities in the Australian Synchrotron, will need major improvements or replacement in coming years. High-temperature superconducting magnets will also be required in high-energy and high-power accelerators of the future. There remains plenty of room for a major program of innovative accelerator research and development with international partners.

12 Available at: http://www.synchrotron.org.au/acasabout/acaswhy

4 Education and training

It is increasingly evident that new growth in developed economies is being driven more and more by knowledge-intensive industries, which need a greater proportion of the population to be educated and trained in science, technology, engineering and mathematics (STEM). To achieve this, every developed economy needs:

- a strong commitment to STEM courses in secondary schooling and universities
- the resources to enable students to access STEM education
- programs for existing workers to enhance their qualifications or expand into careers that require STEM.

Accelerator facilities in Australia can and do play a key role in educating and training people in a broad range of science and engineering skills. Currently, Australian accelerators are used by thousands of people annually to upgrade their skills and carry out their applied and fundamental research.

It is essential for the long-term sustainability of accelerator facilities and capabilities in Australia that we educate and train several quite distinct groups of people associated with the support, operation and research activities of accelerators. These groups should include:

- engineers and technicians to maintain and develop these complex systems and their associated equipment
- researchers and beamline scientists specialising in the operation and running of accelerators for use by the Australian research community
- research innovators to develop new ideas and accelerator-based research programs.

Achieving these outcomes will require a strong university sector, together with industry and government partners. Training needs to attract the best students from around Australia. To achieve this, accelerator laboratories in Australia should have:

- well run, healthy local accelerator facilities with easy access for users
- strong domestic fundamental and applied accelerator research programs
- highly-developed connections with large global accelerator programs and facilities.

The landmark 2010 report, *Accelerators for America's Future*, recognised the value of extensive training and education in accelerator science and engineering as essential.[3]

The report recommended that accelerator science should be recognised as a discipline in its own right, since it is a driver of scientific and technical progress across so many areas of a modern economy:

> *'Continued US innovation in basic accelerator research and in the areas of energy and environment, medicine, industry, security and defense, and science rests on the next generation of accelerator scientists. The motivations for strengthened educational efforts include training of the next generation workforce, engaging the best and the brightest students and early-career scientists and engineers, and workforce training for new applications. Attracting the caliber of scientific minds essential for progress in the field requires a vibrant program of accelerator science and technology research, world-class training facilities and attractive instructional opportunities. Universities should be encouraged to offer courses in the practical uses of industrial accelerator technologies as well as in the discipline of accelerator science.'*

4.1 Technical training for Australians

People involved in accelerator maintenance, operations and development need to be trained across a very broad knowledge base, including engineers and technicians with expertise in:

» high-speed electronics
» high-voltage engineering
» vacuum technologies
» mechanical engineering
» software, IT and logic programming skills related to facility automation
» microwave and radiofrequency instrumentation
» magnetic technology
» fitting and machining
» surveying
» radiation safety.

Training in these disciplines is not just essential for running and maintaining accelerators, but is also highly prized by industry in a multitude of occupations requiring the above skills, which are not directly associated with accelerator facilities. Regular national meetings, such as the Accelerator Technology Forum, which started in 1984 and is run by ANSTO, bring together technical and engineering staff from Australian accelerators to discuss common issues and undertake training and development of new skills.

4.2 Science training for Australians

Researchers who drive the science and innovative technologies associated with accelerators, and use them as their research tools, require training across many scientific disciplines and research areas. These include:

» high-energy, nuclear and atomic physics
» solid state and surface chemistry
» medical physics, biomedical science
» materials science
» environmental science
» accelerator physics and technologies
» X-ray and radiation physics
» electrical and electronic engineering, microwave and radiofrequency systems
» IT and computer sciences.

These are typically in physics and engineering graduate and postgraduate degree courses offered at many universities. Existing organisations, like the Australian Institute for Nuclear Science and Engineering (AINSE) and the Australian Collaboration for Accelerator Science (ACAS), have been excellent coordination hubs for education and training and provide strong linkages to accelerator facilities nationally and internationally.

AINSE was founded in 1958 to help link the work of all Australian universities and several New Zealand universities with the nuclear (and now accelerator) facilities at ANSTO in Sydney. It provides funding and access to ANSTO facilities for undergraduate, postgraduate and postdoctoral students, runs winter schools in reactor and accelerator science, and supports numerous national workshops and conferences every year. It is funded jointly by ANSTO and the Australian Government, and its university members.

ACAS was formed in 2010 by the accelerator facilities in Melbourne, Canberra and Sydney to provide a forum for scientific and technical cooperation. It now runs summer schools in accelerator technology, supports student access to international laboratories like CERN and helps publicise accelerator workshops and conferences.

The Heavy Ion Accelerator Symposium, run annually by the ANU since 2012, is focused on educating and training students, building the user community and developing new and interdisciplinary applications of Australia's heavy ion accelerators, both at a national and international level. The symposium alternates between a national and international focus. ACAS provides support and publicity for the event.

As accelerator facilities in Australia expand—for example, the new $38 million Centre for Accelerator Science at ANSTO, and when new beamlines are commissioned at the Australian Synchrotron—the roles of organisations such as ACAS will need to fill the increased capacity and enlarged user base required for their successful operation. The inclusion of medical facilities and industrial accelerator applications would be beneficial.

Accelerator maintenance staff inside the pressure vessel of the ANU HIAF 15 million volt accelerator. Image courtesy ANU.

4.3 Australia as a global training centre

Australian universities are recognised and valued destinations for the education and training of international students, particularly from Asia. There is an opportunity to enhance and increase these linkages by including expanded access and training at Australian accelerator facilities. This would:

» increase the research base for Australian accelerators

» extend and improve international linkages for accelerator research and technologies

» promote Australian accelerator technologies and knowhow to Asia and beyond.

Several accelerator laboratories in Australia already have significant international training programs coupled to their accelerator facilities.

ANSTO has been working with the International Atomic Energy Agency (IAEA) for decades through Regional Co-operative Agreements (RCAs) with most countries in Asia to train staff in nuclear accelerator-based techniques through extended visits to Australian facilities, and also by running workshops and courses across the Asia–Pacific region.

The ANU Master of Nuclear Science course attracts overseas students, as well as providing new knowledge and expertise to Australian students, both following an undergraduate degree and for mature-age students from the workforce undertaking re-skilling. The ANU undergraduate physics curriculum is also strongly linked to both the ANU Heavy Ion Accelerator Facility and the heavy ion accelerators of the Electronics Materials Engineering Department, through lab programs associated with coursework and undergraduate research projects. These courses are unique in the region, with scores of students annually undertaking projects at the facilities.

Many of Australia's Asian neighbours are entering an economic growth phase that will require increased use of and access to medium- and high-energy accelerators. Australian expertise is valued and sought after, and this should be expanded and encouraged.

5 What does the future look like?

History has consistently shown that when science unscrambles the biggest questions, the answers are striking and often surprising, and lead to societal transformation—new medical treatments, new forms of energy and new forms of technology. Think of the development of quantum mechanics and its current all-pervasiveness in information technology, communications and consumer electronics, for example.

We can be all but certain that another comparable revolution awaits. It will be very exciting, and it will likely be entirely unexpected in nature.

If it is to be transformational, then Australia needs to be a part of it. To ensure its participation in this revolution, Australia must retain and build on its place in the international accelerator community. But what might this exciting future look like?

5.1 World trends in accelerators

Accelerators will continue to become even more ubiquitous than today. We will see more applications of accelerators, with more beam power, more beam energy and more exotic beams. It is foreseen that compact accelerator concepts will be commercialised with increasing use of new materials, such as superconducting electromagnets. We will continue to see more accelerators being built and operated across the spectrum of research, medical, environmental and industrial applications.

There are more than 30 000 accelerators in use in the world today, contributing to our current and future health and technologies. Most are used in medicine and industry, and do not receive the media coverage of large international accelerators developed for research. Nevertheless, they are vital in biomedical research and cancer treatment, in semiconductor research and manufacturing, in energy technology and much more.

A commercial, high-volume ion implantation instrument for semiconductor manufacture. Image courtesy Applied Materials.

The various accelerator technologies now applied in many areas were originally driven by the requirements of fundamental research. This theme continues today, with nationally-funded institutions in many countries such as France, Germany and Japan developing new technologies to make accelerators for research smaller, cheaper and much more capable. These developments will flow on to benefit and stimulate the broader uses of accelerators worldwide.

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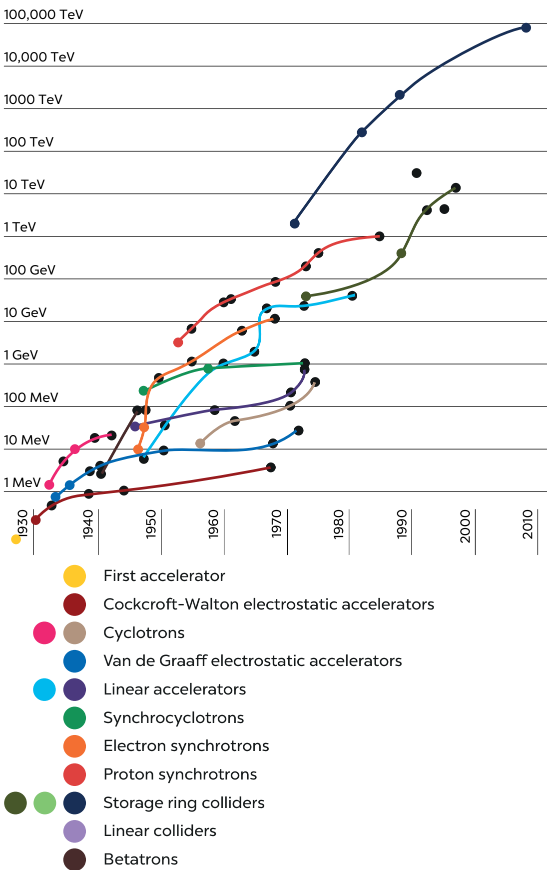
Developments currently occurring in some fields require accelerators that are increasingly complex and expensive. This can be the case in research, for example in high-energy physics, nuclear physics and photon sources. It can also be true in the medical field, where hadron therapy accelerator systems using proton or carbon beams cost more than $200 million.

In these areas, national and in some cases international collaboration is essential, both to fund new facilities and maximise the outcomes from their development.

In other areas, technological developments are cutting the cost of accelerators that can provide the required capabilities, such as in accelerator mass spectrometry, materials research and industry. Here, accelerator numbers have been growing rapidly, and computerisation is also increasing productivity.

One aspect of accelerator performance (among many important characteristics) is the maximum energy that can be provided. Physicists continue to develop new accelerators to provide higher and higher energies, and have done so for more than 80 years.



The Livingston Plot shows worldwide advances in high-energy accelerators. Image courtesy *symmetry* magazine.

The Livingston Plot, first created in 1954, shows how worldwide advances in high-energy accelerators had occurred and where they would be headed, based on known physics.

Originally developed by Milton Stanley Livingston, co-inventor of the cyclotron and one of the founders of modern large-scale particle accelerators, it has since been updated and shows the continued path of future accelerator energy increases. The plot shows a strong record of improvement, and that new machines increase their maximum beam energy by roughly an order of magnitude every six years.

To achieve these advances, accelerator science is constantly pushing the envelope of the accelerating gradient, particularly with linear accelerators. The higher the electric field gradient, the greater the energy of the final beam, or the smaller the accelerator for a given energy. When it comes to the discovery of new particles or particle interactions, the beam energy needs to be as high as possible, but in medical accelerators the smaller the accelerator the better. Since the energy of the final beam is determined by the maximum distance of the tumour from the body's surface, which is limited by human anatomy, new technology should reduce size and costs, making improved treatments modes more accessible.

Developments are also progressing in circulating accelerators to increase their magnetic field strength, which is one of the key parameters that define the ring diameter of the accelerator for a given energy, or the maximum energy for a given size ring. High-field superconducting magnets are one solution for the High Energy Large Hadron Collider upgrade, and a new 100 TeV 100 km collider that should supersede the current LHC at some stage in the future, while high-field room temperature superconducting magnets will benefit synchrotron light sources.

Research is also continuing into how to increase the beam intensity and power of accelerators, increasing the total number of particles that can be generated, captured, accelerated and stored. This is important in the generation of radiopharmaceuticals, in the transmutation of radioactive waste and in the production of radioactive isotope beams, each of which requires very high-intensity primary beams.

In single atom counting (AMS), the reduction in the cost of typical accelerators is resulting in a continuing increase in the number of AMS laboratories around the world. Some areas such as Europe and Japan are now well equipped. Other regions such as parts of South America, Asia and Africa have very limited or no capability. Because of the numerous applications of AMS in fields such as environment, earth sciences, biomedical and now astrophysics, AMS labs will continue to proliferate, with the accelerators themselves and the sample preparation capability being equally important.

Future advances in the AMS field will come from new applications, driving the development of new techniques to accelerate, separate and count new cosmogenic radioactive isotopes for which methods have not yet been developed. Those laboratories which have played a significant role up to now in driving the field forward (notably the ANU Heavy Ion Accelerator Facility and ANSTO), will have the advantage of experience and technical support in devising new methods. A challenge will be for researchers in diverse fields to communicate new requirements to those able to develop the new techniques to meet them. Australia is well placed in this regard, having a long history of such collaborative developments.

5.2 What new technologies are on the horizon?

Two international collaborations are currently leading the next generation of large-scale projects: the International Linear Collider (ILC) and the Compact Linear Collider (CLIC). They complement the LHC by colliding electrons and positrons instead of the LHC's protons, which gives access to a different set of collision products to examine.[13] Muons would also make a valuable beam for research purposes. They are fundamental particles like electrons and positrons, but are approximately 200 times heavier and could be accelerated and collided—if we can solve the problem of generating a continuous beam from particles that decay so quickly.

Different approaches to generating high energy collisions also need to be explored. Resource constraints will prevent accelerators from simply getting bigger and bigger so alternative means of generating stronger electric fields are being proposed. One of the most promising future accelerator concepts is the plasma wake-field accelerator which will be further evaluated in the coming years.[14]

The completion of international-scale high-intensity radioactive isotope beam (RIB) accelerators in the next 5–10 years will not only provide a revolutionary capability for nuclear physics and astrophysics research. The future availability of a vastly larger range of radioactive isotopes, each with its own individual cascade of radioactive decays, offers new prospects for applications in the many fields where radioactive isotopes are now used. The US facility FRIB, due for completion in 2022, will provide research quantities of rare isotopes that can be used to develop new medical diagnostics and treatment of disease.

Extreme light infrastructure

A European collaboration is working to build some of the most intense laser beam systems in the world. The Extreme Light Infrastructure (ELI) project is a pan-European project to develop new laboratories for new applications of ultra-intense laser beams.

One application is to develop the process of laser wakefield acceleration. The passage of intense ultra-short duration laser pulses through a plasma generates extremely high accelerating gradients. This offers the potential to build compact accelerators in the future.

Another major project is to collide a high-intensity accelerated electron beam with a very intense laser beam. Through the Compton back-scattering of photons from the electrons, a unique very bright high energy (up to 20 MeV) X-ray photon beam can be produced. This will allow investigation of new fields of fundamental physics, new nuclear physics and astrophysics topics, and will support applications in material science, life sciences and nuclear materials management.

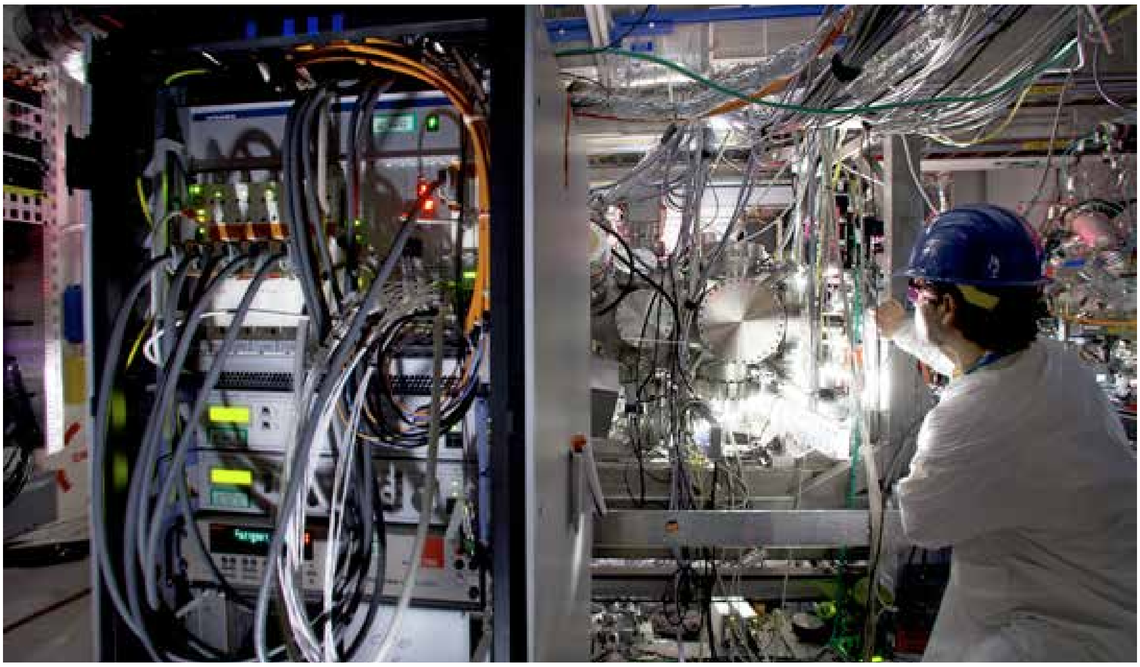
The production of high-intensity light for scientific research and applications from infrared to hard X-rays at synchrotron and storage ring accelerator facilities—commonly known as light sources—is well developed worldwide. In line with the international light source experience, the user base at the Australian Synchrotron is broadening and the experiments are becoming more sophisticated, requiring greater stability, shorter pulses and higher coherence.

New technical developments to produce femtosecond X-ray pulses (one millionth of one billionth of a second), single bunch timing experiments, tuneable repetition rate picosecond pulses and laser-like beams are moving researchers into the ultrafast and high resolution domains. This will unlock new science that is not yet possible with a conventional synchrotron light source facility.

Better light sources will also mean we need better detectors; it is no good being able to produce high brightness short pulse photons if we are not able to measure them. The resulting new photon detectors will not only improve data collection at conventional light sources but

13 ILC: www.linearcollider.org/ILC; CLIC: http://clic-study.web.cern.ch/

14 Litos et al 2014, High-efficiency acceleration of an electron beam in a plasma wakefield accelerator Nature 515, 92–95.



An example of large-scale advanced accelerators from around the world is the SLAC National Accelerator Laboratory at Stanford University, California (Photo by Brad Plummer.) Image courtesy SLAC National Accelerator Laboratory.

are paving the way towards the next generation of photon sources, namely X-ray free-electron lasers, or XFELs (see Chapter 1). Ultra-short, intense X-ray pulses will become a new tool with which to probe the mechanisms of chemical reactions, including their reaction intermediates, and so better understand how to manipulate them. XFELs is expected to be particularly exciting for investigating biomolecules that are difficult to examine using conventional methods.

While Australia does not yet have the resources to be an early adopter of this technology, the time will soon come when it is within our financial reach. In the meantime, Australian researchers are succeeding in winning competitive time on overseas FELs and advancing their expertise with this new technology.

Even further afield in the realm of light source technology are tabletop accelerators that may be able to deliver the same performance as a free-electron laser. As for particle physics accelerators, the front-runners in this capacity are laser-driven plasma-wakefield accelerators. Another concept for users of light sources is the so-called 'accelerator on a chip'—a glass chip the size of a grain of rice which is designed with nanoscale ridges that interact with the electric field of a laser and boost the speed of the electron stream as it passes through the chip[15,16].

While both these developments are in their technical infancy, they have demonstrated that tabletop accelerators are feasible in principle.

In applications of accelerators, radiation detectors play a crucial role—sometimes as crucial as the accelerators themselves. Each type of radiation requires a different type of detector. As seen in the massive ATLAS detector at CERN—which Australian researchers contributed to building—the effort and cost to develop optimised detector systems can approach the cost of the accelerator itself. This underlines the importance of detector instrumentation.

In funding scenarios for future Australian accelerator capabilities, planning and defining the budget should not only include the accelerator itself, but also the full suite of instrumentation. Without the beamline instruments, the full benefit from investment in the accelerator cannot be realised.

The development of detector systems for accelerator-based research has practical applications. In the medical field, developments in nuclear detector technology and semiconductor production methods are being translated to micro- and nano-scale dosimeters for medical radiation dose validation. Australia is playing a significant part in this, with the Centre for Medical Radiation Physics at the University of

15 http://www.forbes.com/sites/alexknapp/2013/09/29/researchers-build-a-particle-accelerator-on-a-chip/

16 E.A. Peralta et al. (2013), "Demonstration of electron acceleration in a laser-driven dielectric microstructure", *Nature* 503: 91–94. http://www.nature.com/nature/journal/v503/n7474/full/nature12664.html

Wollongong using Australia's accelerators to test its newly-developed detectors.

Another application, this time of detectors originating in particle physics, is in muon tomography. Cosmic ray muons, which are present at the Earth's surface everywhere, have been used for many decades to radiograph large objects. The technique of muon transmission imaging was first used in the 1950s by E. P. George to measure the depth of the overburden for a tunnel in Australia[17]. Detector and computational developments from fundamental research have allowed the development at Los Alamos in the US of the improved technique of muon-scattering tomography. This tracks both the incoming and departing trajectories of muons to 'see inside' closed/sealed objects. This has been used for non-invasive security and nuclear and non-proliferation applications. The technique is useful for probing large objects, particularly when considerable time is available to make measurements (a result of the relatively low flux of cosmic ray muons and small scattering probabilities). With this proviso, the advantage is that no source of radiation needs to be provided; instead nature provides.

5.3 What should Australia's accelerator future look like?

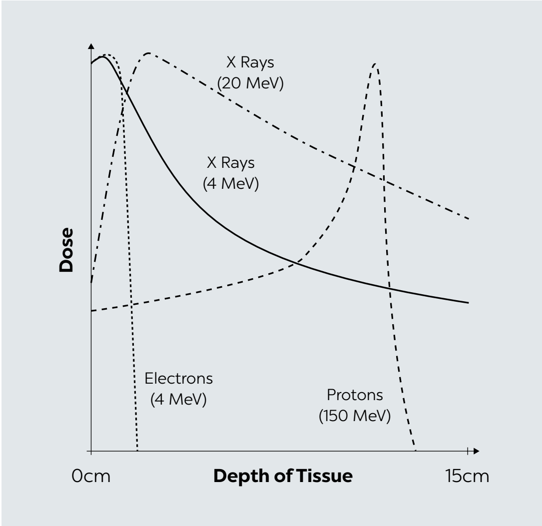
i. Infrastructure

Local accelerator facilities need to be enhanced to stay at the leading edge, and future research accelerators require a global effort to realise ambitious design goals. Australia is showing strong results from research into low-emittance electron storage rings, critical achievements required for future synchrotron light sources and damping rings for high-luminosity linear colliders for high-energy physics.

There is also an opportunity to create test facilities at Australian accelerator laboratories. Test facilities are few in number globally and in high demand. Such test facilities would be unique in the region. Accelerator components, innovative detector systems and new research ideas can be developed and tested in Australia to provide proof-of-principle experimental results and guide future design directions internationally. This model is already proving successful in research fields based on Australia's heavy ion accelerators.

Australia needs to be strongly engaged with the world's newest accelerator facilities, accelerator technologies and accelerator applications to benefit from such new developments. This can be through collaborative use of international-scale facilities constructed overseas, and through maintaining and developing world-class capability within Australia's accelerator infrastructure.

ii. Hadron therapy



The dose deposition in water by X-rays, electrons and protons. The dose deposition by protons for cancer therapy is superior to that of X-rays and electrons as most of the energy can be deposited within the tumour volume, sparing the adjacent healthy tissues. Image courtesy Eva Bezak.

Because of their physical and radiobiological properties, heavy ions and protons are beneficial in treatment of complex anatomical structures and radio-resistant tumours.[18] The benefit of hadron radiotherapy has been demonstrated in many cases. These include: advanced head and neck tumours, advanced bone and soft tissue cancers, locally-advanced prostate cancers, cancer of the skull base and cervical spine, eye melanoma and oesophageal cancer.

Statistics show that in Australia, proton or heavy ion therapy can be indicated for 700 patients annually, for whom it is the only beneficial treatment option. At present the only possibility for such patients is to receive treatment overseas at very high costs or undergo a less effective treatment. This figure does not include childhood cancers or cancers of young adults, increasing further the pool of patients who would benefit from hadron therapy. The benefit

17 George, E.P. 1955. "Cosmic rays measure overburden of tunnel", *Commonwealth Engineer*. 455–57.

18 Allen, Bezak and Marcu 2013 *op cit*

of hadron therapy in these cases is to reduce the radiation dose to surrounding tissue, minimising possible cognitive difficulties, and radiation-induced malignancies later in life. The greatest experience is currently with proton therapy, the use of heavy ions still being considered experimental. There is limited government funding to send some of the eligible paediatric patients to receive proton therapy in the US.

Australia needs to seriously consider adopting this technology in the near future, otherwise when measured against comparable advanced economies it risks being left behind in cancer radiotherapy. And this translates to poorer prospects for Australian cancer sufferers. If Australia were to build such a facility, it would be the only dedicated clinical unit in the Southern Hemisphere offering hadron therapy. This might lead to new medical links with other countries in the region.

Several state organisations and private consortia are preparing the case for proton and heavy ion treatment facilities, and are lobbying for support and funds. Ideally, the Australian Government would assume an active role in co-ordinating and planning, and in contributing to the funding and building, of such facilities.

Planning of such a capability requires a national approach, and its implementation will enhance Australia's ability to conduct cancer treatments and research at the forefront of radiation science and medicine. Any existing accelerator facilities (ANU, Australian Synchrotron and ANSTO) will be essential in terms of provision of a suitably trained accelerator workforce and the identification of investment in infrastructure.

iii. More medical linear accelerators

Another issue that requires urgent attention is the number of medical accelerators available in Australia. Linear accelerator technology has been a staple for cancer therapy in Australia since the 1950s. Over the years, the X-ray energies produced by linacs have increased from 4–18 MeV, and at present linacs are the primary radiotherapy tools.

In Australia, management and control of cancer is a national health priority area. In 2010 cancer was estimated to account for 19% of the total health burden[19]. Radiation therapy is used to treat most cancers within the body, and contributes approximately 40% to the cure of cancer[20]. While there are significant initial capital costs to set up a radiation oncology centre with linear accelerators, over the course of its service, radiation therapy is one of the cheapest and most cost effective cancer therapies available. In most cases, it is delivered as an outpatient treatment, further reducing costs[20].

By 2020, the number of cases of cancer diagnosed in Australia is expected to reach 150 000, an increase of almost 40% from 2007[21]. More than 50% of all new cancer patients will require radiotherapy, but already there is evidence that patients have difficulty accessing radiation oncology services. Australia needs 267 linacs by 2022 to achieve the internationally-accepted optimal utilisation rate (approximately an extra 100, in addition to the replacement of the current fleet)[22].

19 AIHW 2010. *Cancer in Australia 2010: an overview*. Cancer series no. 60. Cat. no. CAN 56. Canberra: AIHW. http://www.aihw.gov.au/publication-detail/?id=6442472459

20 The Royal Australian and New Zealand College of Radiologists (2012) Planning for the Best: the Tripartite National Strategic Plan for Radiation Oncology (Australia) 2012–2022, 1–135

The cost per year of life gained from radiotherapy treatment in Australian dollars (1993 dollars) was reported to be A$7186. The addition of radiation therapy to breast-conserving surgery has been shown to improve quality of adjusted life years (QALYs) at a cost of $28 000/QALY and the use of short-term, pre-operative radiation therapy for operable rectal cancer has been shown to increase QALYs by 39% at a cost of $25 100/QALY. These costs are less than the threshold of $50 000/QALY commonly cited for cost-effective care

21 AIHW 2012. *Cancer incidence projections: Australia*, 2011 to 2020. Cancer, Series no. 66. Cat. no. CAN 62. Canberra: AIHW. http://www.aihw.gov.au/WorkArea/DownloadAsset.aspx?id=10737421440

22 Projecting the radiation oncology workforce. Input to the Tripartite National Strategic Plan For Radiation Oncology in Australia. Report to The Royal Australian and New Zealand College of Radiologists, The Allen Consulting Group (2012); Delaney GP., Jacob S., Featherstone C., Barton MB. Radiotherapy in cancer care: estimating optimal utilisation from a review of evidence-based clinical guidelines. Collaboration for Cancer Outcomes Research and Evaluation (CCORE), Liverpool Hospital, Sydney, Australia, 2003 http://canceraustralia.gov.au/sites/default/files/publications/radiotherapyreport1_504af01e8daf0.pdf

6 Conclusions and recommendations

6.1 Encapsulating the vision

Accelerators are now ubiquitous throughout the technological world, and there are few areas of daily life that are not in some way touched and improved by their existence. Whether it is the superpower of the Large Hadron Collider, radioisotopes that shrink tumours, or the electron beams used to clean coal emissions, accelerators are a fundamental technology for the future.

As transformative as accelerators have been, their and our journey is in many ways just beginning. We are now getting glimpses over the horizon, and the view is exciting and challenging in equal measure. The benefits of hadron therapy in cancer treatment are already being reaped overseas, while the application of accelerator science to improve safety and efficiency of nuclear power is starting to become a reality.

For a relatively small nation, Australia has held its own in the international field of accelerator science. We have world-class facilities and have fostered world-class scientific talent in their use. Australian scientists have also made significant contributions to global collaborations in the field of accelerator science. With a greater emphasis on collaboration across national and geographic boundaries, now more than ever Australia needs to become strongly engaged within our region, and enhance its place in the global scientific community.

But progress is moving at a rapid pace. Australia risks losing its hard-fought gains in accelerator science if we do not act now to ensure the long-term viability of existing infrastructure, and lay a solid foundation for embracing the new wave of accelerator innovation.

A sustainable plan for new accelerator projects

With so many new developments and potential applications for accelerator science and technology on the horizon, Australia needs a plan for the future of accelerator infrastructure. The continued development of the Australian Synchrotron and its successors must be a top priority. Funding to keep small-to-midsized facilities up to date is also required. These facilities enable vital work in the national interest in areas such as accelerator mass spectrometry and nuclear and materials science, and they cannot be neglected.

And with the benefits promised by hadron therapy, Australia should take a national approach to assess and coordinate planning, not only for the development of hadron therapy facilities, but also to provide the necessary expertise and support personnel in the longer term. This is true of all new investment in technology, which is nothing without the expertise to use it. We do need to ensure there is ongoing support for PhD-level training in research and development aimed at improving accelerator capabilities, and also provision for training in the specialised technical skills needed in the field.

Finally, we need to make sure that a meaningful and appropriate Australian research presence at large international facilities is preserved and financially supported, to keep up-to-date with and benefit from massive international investments in new research capabilities.

A new national advisory group

To make a national plan for accelerator infrastructure, the priorities and time scales for investment in new Australian capability need to be assessed. A national advisory group of recognised experts from a diverse range of accelerator-based activities would be ideal. This group would ensure that not only is the full spectrum of accelerator-related activities considered, but that there is national coordination to avoid duplication and inefficiency.

This advisory group would assess the status of existing programs and projects, identify gaps in accelerator-based capability, access and training, and provide strategic advice on a national program of accelerator investment. The group would also work to maximise the quality and quantity of international collaborations, with a focus both on external use of Australian facilities and Australian use of overseas facilities.

Some of these functions are currently being performed by the Australian Collaboration for Accelerator Science, founded in 2010, which has already made a significant contribution in organising teaching and training activities for students all the way up to existing accelerator staff. It has also provided a valuable forum to enable and encourage discussions of current and future plans in accelerator research and development, and is working to coordinate the deployment of the latest computer software and hardware across the accelerator physics community.

A sustainable funding model for existing infrastructure

Stable, ongoing Commonwealth funding supporting the operations costs of national facilities is essential to maintain an effective and efficient Australian program in accelerator-based science. The ideal scenario would be continuing operations support, with periodic reviews, for major facilities and programs such as the Australian Synchrotron, ANSTO accelerators, and university heavy ion accelerators. Individual research projects using these facilities would be funded under existing competitive grant schemes. A stable funding program to support the costs of accessing international facilities not available in Australia should also be in place, on the same basis.

Further opportunities for improvement

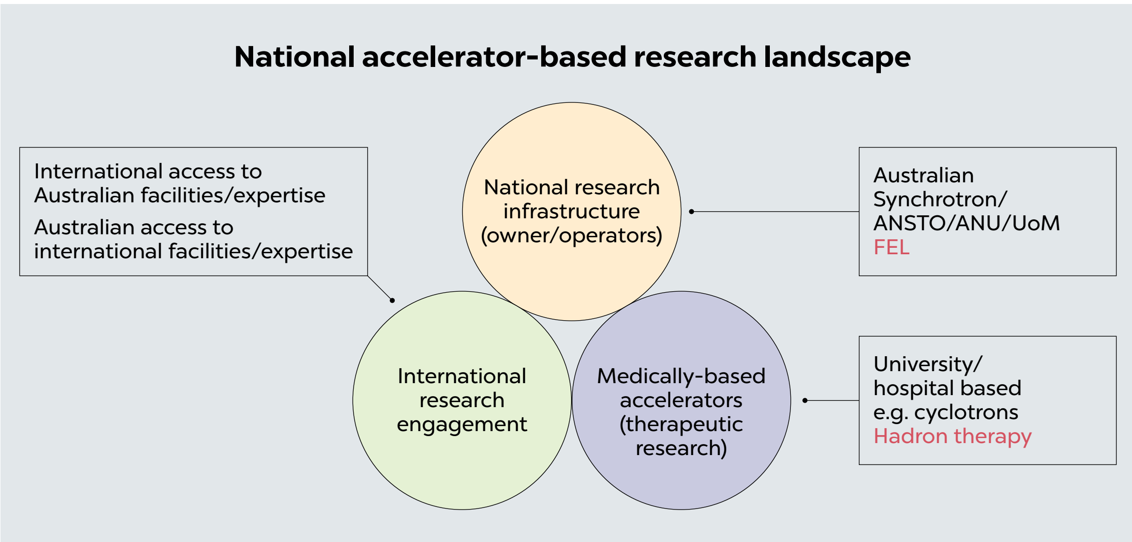
To participate fully in the future of accelerator-based science, Australia would benefit not only from a long-term plan that maps out the development of our accelerator infrastructure, but also from a plan to give better security to those who work within it.

We also need a stronger research program in accelerator science itself, to keep Australia on the frontline of developments and maintain our international standing in accelerator-based science and technology. Similarly, we need to lay the groundwork for inspiring, nurturing and training the next generations of accelerator scientists.

A forum for education and training in accelerator science would ensure that we have world-class scientists with the specialised technical skills needed to develop and exploit new investments in accelerator technology.

Given the speed at which progress is being made in this area, accelerator-based science would benefit enormously if it were assigned as a research priority for Australian science.

Huge opportunities are coming our way, and now is the time to ensure that we are in a position to take full advantage of them.



The national landscape of accelerator-based research. Red text indicates desirable, future capabilities.

6.2 Recommendations

Australia sits at a major crossroad with respect to accelerator science. With a sound base of expertise and infrastructure, we are poised to take full advantage of the scientific and technological revolution in accelerator science emerging from major international collaborations. However, Australia will not be able to fully realise the health, economic, defence and other benefits of these new developments without a deliberate and strategic approach led by government, health authorities and research funding agencies to ensure that our base expertise and infrastructure is adequately supported and upgraded. Consequently, **this report recommends that**:

1. State and federal health departments work together to assess the value and the feasibility of investing in the technology, infrastructure and expertise needed for a national capability in **hadron therapy for cancer treatment**. Such a capacity would potentially have multiple benefits, including improving health outcomes and reducing overall cancer management costs, especially for patients who have no other treatment option, and establishing Australia as a regional capability centre in hadron therapy.
2. The recommendations of the Clark Research Infrastructure Review are implemented in a way that ensures **ongoing operations funding** for Australia's existing world-class accelerator infrastructure through NCRIS or any future program responsible for research infrastructure. Furthermore, that a national funding program for large-scale infrastructure projects be established with the capacity to keep Australia's national accelerator infrastructure up to world standard.
3. Australian universities develop an **outstanding program in accelerator R&D** to attract high quality PhD students. This program will improve Australia's accelerator capability, supporting training in the specialised technical skills needed to exploit new investment in accelerator technology, and position the nation to exploit the opportunities opening up in this critical area.
4. Dedicated funding through the Government's proposed International Science Engagement Strategy to allow Australian accelerator researchers and research facilities to **partner with international facilities** such as the proposed US$10 billion International Linear Collider and the Linac Coherent Light Source in California—thus helping to develop high-tech local industry.
5. That current and future bodies responsible for development and operation of Australia's major national research infrastructure **liaise closely with the Australian Collaboration for Accelerator Science and relevant National Committees of the Australian Academy of Science** for advice and recommendations on issues relating to strategic directions, funding priorities and technical issues pertaining to accelerator facilities and capability in Australia.

Appendix 1:
Expert Working Group Membership

Professor David Hinde FAA, Co-Chair	Department of Nuclear Physics, The Australian National University
Professor Keith Nugent FAA, Co-Chair	La Trobe University
Professor Elisabetta Barberio	School of Physics, The University of Melbourne
Professor Eva Bezak	School of Health Sciences, University of South Australia
Associate Professor Mark Boland	Australian Synchrotron and The University of Melbourne
Professor David Cohen	Australian Nuclear Science and Technology Organisation (ANSTO)
Professor Rob Elliman	Department of Electronic Materials Engineering, The Australian National University
Professor Keith Fifield	Department of Nuclear Physics, The Australian National University
Dr Lizbeth Kenny	Royal Brisbane and Women's Hospital, Queensland Government
Professor Andrew Peele	Australian Synchrotron and La Trobe University
Professor Geoff Taylor FAA	ARC Centre of Excellence For Particle Physics at the Terascale, The University of Melbourne

Invited Contributors:

Professor David Jamieson	The University of Melbourne
Professor Andrew Stuchbery	The Australian National University