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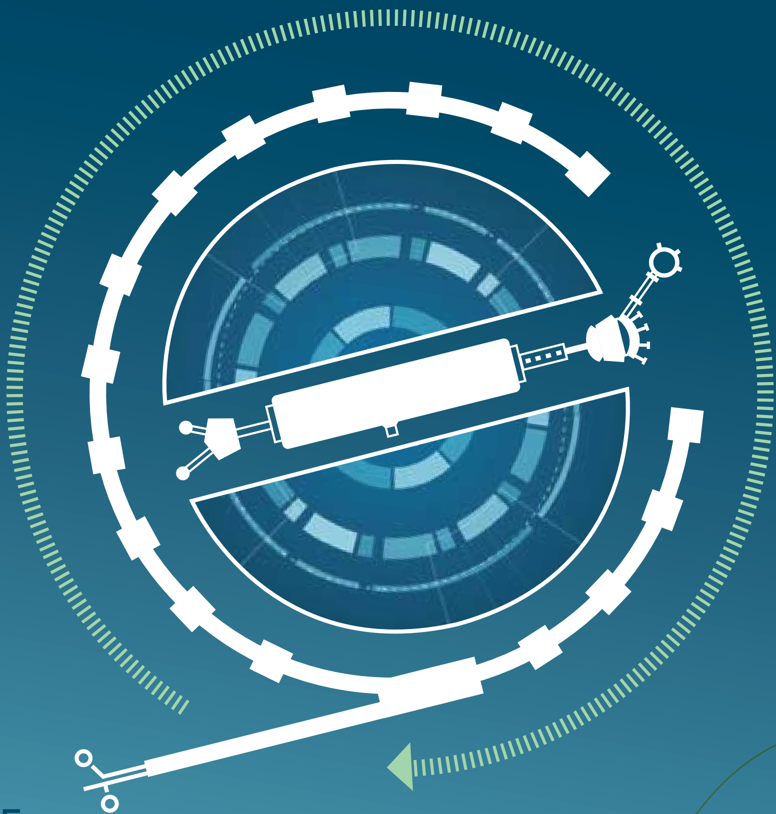
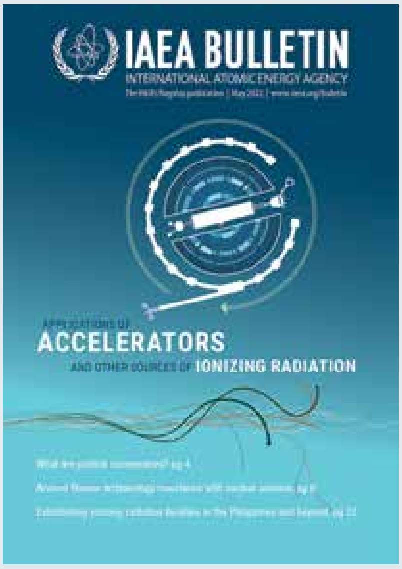


APPLICATIONS OF ACCELERATORS AND OTHER SOURCES OF IONIZING RADIATION



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IAEA

The International Atomic Energy Agency's mission is to prevent the spread of nuclear weapons and to help all countries — especially in the developing world — benefit from the peaceful, safe and secure use of nuclear science and technology.

Established as an autonomous organization under the United Nations in 1957, the IAEA is the only organization within the UN system with expertise in nuclear technologies. The IAEA's unique specialist laboratories help transfer knowledge and expertise to IAEA Member States in areas such as human health, food, water, industry and the environment.

The IAEA also serves as the global platform for strengthening nuclear security. The IAEA has established the Nuclear Security Series of international consensus guidance publications on nuclear security. The IAEA's work also focuses on helping to minimize the risk of nuclear and other radioactive material falling into the hands of terrorists and criminals, or of nuclear facilities being subjected to malicious acts.

The IAEA safety standards provide a system of fundamental safety principles and reflect an international consensus on what constitutes a high level of safety for protecting people and the environment from the harmful effects of ionizing radiation. The IAEA safety standards have been developed for all types of nuclear facilities and activities that serve peaceful purposes, as well as for protective actions to reduce existing radiation risks.

The IAEA also verifies through its inspection system that Member States comply with their commitments under the Nuclear Non-Proliferation Treaty and other non-proliferation agreements to use nuclear material and facilities only for peaceful purposes.

The IAEA's work is multi-faceted and engages a wide variety of partners at the national, regional and international levels. IAEA programmes and budgets are set through decisions of its policymaking bodies — the 35-member Board of Governors and the General Conference of all Member States.

The IAEA is headquartered at the Vienna International Centre. Field and liaison offices are located in Geneva, New York, Tokyo and Toronto. The IAEA operates scientific laboratories in Monaco, Seibersdorf and Vienna. In addition, the IAEA supports and provides funding to the Abdus Salam International Centre for Theoretical Physics, in Trieste, Italy.

Accelerators and radiation technology for sustainable development

By Rafael Mariano Grossi, Director General, IAEA

"Protons give an atom its identity, electrons its personality," is the way in which author Bill Bryson once colourfully described the fabric of all matter. It is an appropriate description of the building blocks of the universe. Each atomic particle, chemical element, and isotope reveals something about the nature, past, and potential of the matter it forms. Accelerators and other radiation technologies are invaluable tools when it comes to studying and working with atoms.

Accelerators come in many shapes and sizes and today there are more than 20 000 of them operating worldwide. They help create radiopharmaceuticals, cure diseases, preserve food, monitor the environment, strengthen materials, understand fundamental physics, study the past, and even solve crimes.

This edition of the *IAEA Bulletin* explores different types of accelerators and examines the many ways the IAEA supports their applications in health, agriculture, research, environment and industry. Many accelerator techniques work and deliver such diverse benefits by applying different types of radiation. A host of industrial applications using accelerators and radiation sources are critical to the global economy and to pursuing sustainable development.

The IAEA's laboratories in Seibersdorf, Austria, support researchers from around the world in using ionizing radiation in various ways. These include its application to develop crops resilient to environmental stresses; and to sterilize male insects used in a special pest control technique, that suppress mosquitos, tsetse flies, and fruit fly populations in Latin America, Africa, Asia and Europe.

Further examples in this Bulletin describe ways ionizing radiation has helped preserve an ancient ship; how it is used to repurpose and recycle plastics; how it can protect food from decay and pests; and how it helps to authenticate and date objects.

At the IAEA, we are helping to foster innovation in accelerator and radiation technologies. To this end, we are hosting two important conferences this year the International Conference on Accelerators for Research and Sustainable Development, the very first of its kind; and the Second International Conference on Applications of Radiation Science and Technology, a gathering that will look beyond accelerators with insight on the greater scope of ionizing radiation sources out there.

At these events, the communities that use and most benefit from these technologies will gather, to share their experiences and best practices, and in this way to advance and propagate science for development.

As society looks to science to solve great and existential challenges, scientists are looking to accelerators and their applications for answers. As they do, the IAEA is there with them, working to ensure countries from all continents have access to this powerful and beneficial nuclear application.

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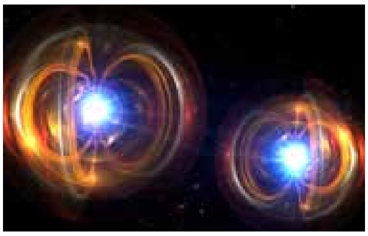
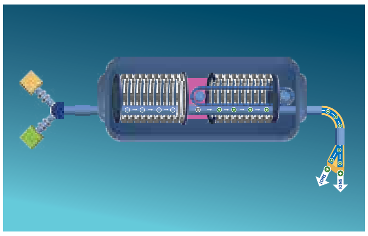
(Photo: A. Abrunhosa/University of Coimbra)

(Photos: IAEA)





What are particle accelerators?

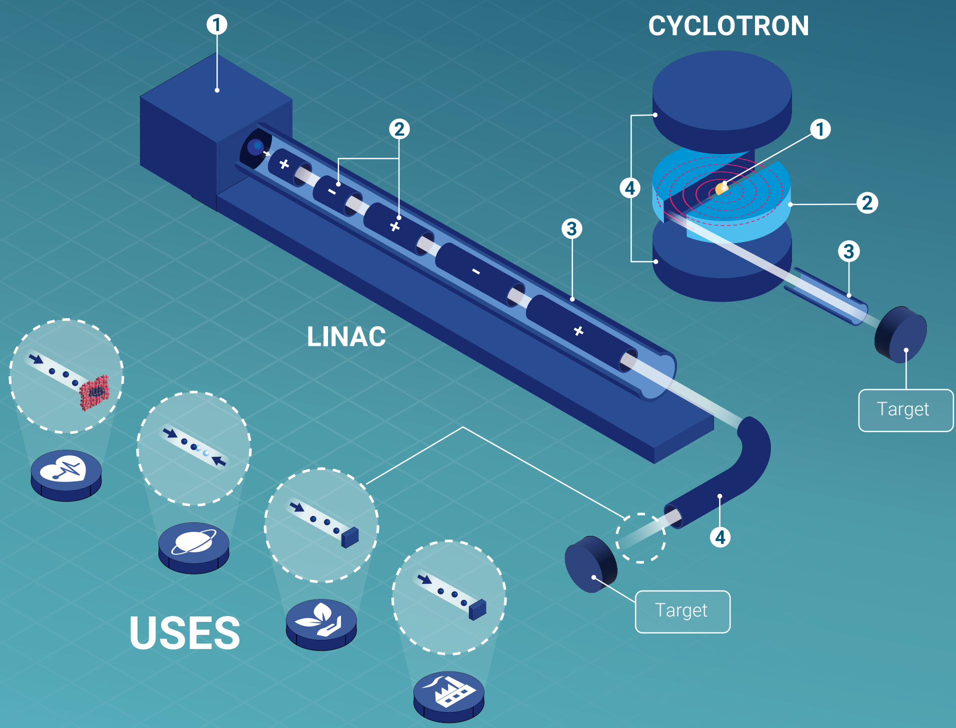
By Sotirios Charisopoulos and Wolfgang Picot

FUNDAMENTAL PARTS OF A PARTICLE ACCELERATOR

Particle accelerators produce and accelerate beams of charged particles, such as electrons, protons and ions, of atomic and sub-atomic size. They are used not only in fundamental research for an improved understanding of matter, but also in a plethora of socio-economic applications related to health, environmental monitoring, food quality, and energy and aerospace technologies, among other fields.t

Particle accelerators can be linear (straight) or circular in shape and have many different sizes. They can be tens of kilometres long or fit in a small room, but all accelerators feature four principal components:

1. A source which produces the charged particles;
2. A composite device to add energy to the particles and speed them up by applying a static or oscillating electric field;
3. A sequence of metallic tubes in a vacuum to allow the particles to move freely without colliding with air molecules or dust, which can dissipate the beam;
4. A system of electromagnets to steer and focus the beam particles or change their trajectories before being bombarded into a target sample.



USES OF PARTICLE BEAMS

HEALTH

Beams are used to sterilize medical equipment and produce radioisotopes required to synthesize radiopharmaceuticals for cancer diagnosis and therapy. Large accelerators can destroy cancer cells, reveal the structure of proteins and viruses, and optimize vaccines and new drugs.

RESEARCH

Some accelerators — the largest ones — are used to make sub-nuclear particles collide to advance our knowledge of the universe. Some of these accelerators are also used to produce neutrons.

ENVIRONMENT

Typically, proton beams can be used to detect trace chemical elements in the air, water or soil. For example, they can reveal the concentration and composition of the different pollutants and provide a unique signature of the air quality.

INDUSTRY

Beams can interact with the atoms of a target material — for example, to make the material more durable.

TYPES OF PARTICLE ACCELERATORS

ION IMPLANTERS

Ion implanters are widely used in industry to, for example, make materials more resistant to damage from wear and usage. Around 12 000 ion implanters around the world help fabricate semiconductors for smartphones and solar panels. and harden metal, ceramic and glass finishes. Ion implanters can also improve the reliability of materials used for medical implants.

ELECTRON BEAM ACCELERATORS FOR INDUSTRY

There are almost 10 000 electron beam accelerators in operation globally. They can, for example, help make materials more durable in extreme temperatures, or resistant against chemicals. Electron beams are also used for sterilizing medical products and foods, and to disinfect sewage water. They are used widely in the automotive and aerospace industries, for machine construction, and by medical product manufacturers.

LINACS

Linear accelerators (linacs) may vary in length, from a couple of metres to a few kilometres long. Many of them are used in scientific research. Medical linacs installed at hospitals, create bursts of X-rays that are guided towards tumour cells to destroy them. There are about 1000 medical linacs operating worldwide.

CYCLOTRONS

More than 1200 cyclotrons around the world create proton or deuteron beams for medical uses. They produce radioisotopes that are used for medical imaging to diagnose and treat cancers. Many cyclotrons are located at hospitals for producing radiopharmaceuticals with short-lived radioisotopes.

SYNCHROTRONS

The more than 70 synchrotrons worldwide are the giants among particle accelerators. They are used for scientific research and help us understand the fundamental laws of our universe. Scientists use synchrotrons to study chemistry, biomedicine, natural and cultural heritage, the environment, and much more.

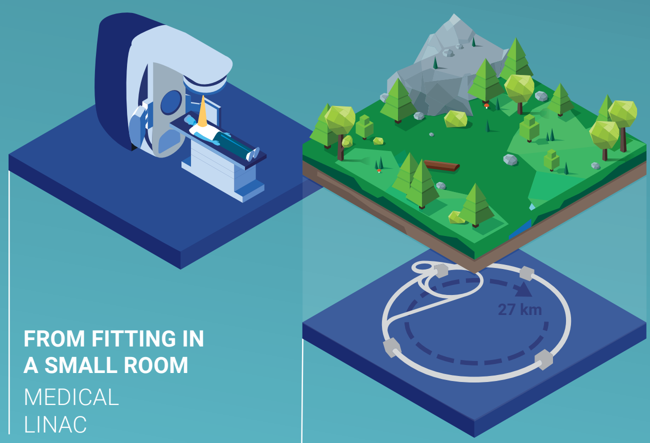
ELECTROSTATIC ACCELERATORS

Electrostatic accelerators, notably tandem accelerators, are less expensive, and scientists use them to investigate material properties, monitor the environment, support biomedical research, study cultural heritage objects, and more. Experts expect the current 300 machines worldwide to grow in number over the coming years.

TODAY THERE ARE MORE THAN

20 000

ACCELERATORS IN OPERATION WORLDWIDE



SIZE

FROM FITTING IN A SMALL ROOM
MEDICAL LINAC

TO TENS OF KILOMETRES
SYNCHROTRON

(Graphics: A. Vargas Terrones/IAEA)

Understanding the environment and addressing pollution using accelerators

By Lenka Dojcanova

Elettra-Sincrotrone Trieste in Italy.
(Photo: Elettra-Sincrotrone Trieste)

Heavy metals and other toxic chemicals can pollute air, water and soil and, consequently, harm flora and fauna. To counteract such elements, scientists first need to better understand their behaviour. Accelerators help in this effort by using charged particle beams to strike selected materials to either analyse or modify their surface, composition, structure or other properties.

"Accelerator-based techniques offer unique capabilities and provide powerful insights into pollution in a fast, non-destructive and cost-effective way," said Román Padilla, Nuclear Instrumentation Physicist at the IAEA. "Particle accelerators used for understanding and improving the environment come in all shapes and sizes, and accelerator-based ion beam methods, in particular, can help us characterize samples from soils, sediments, biota, water or fine air particles."

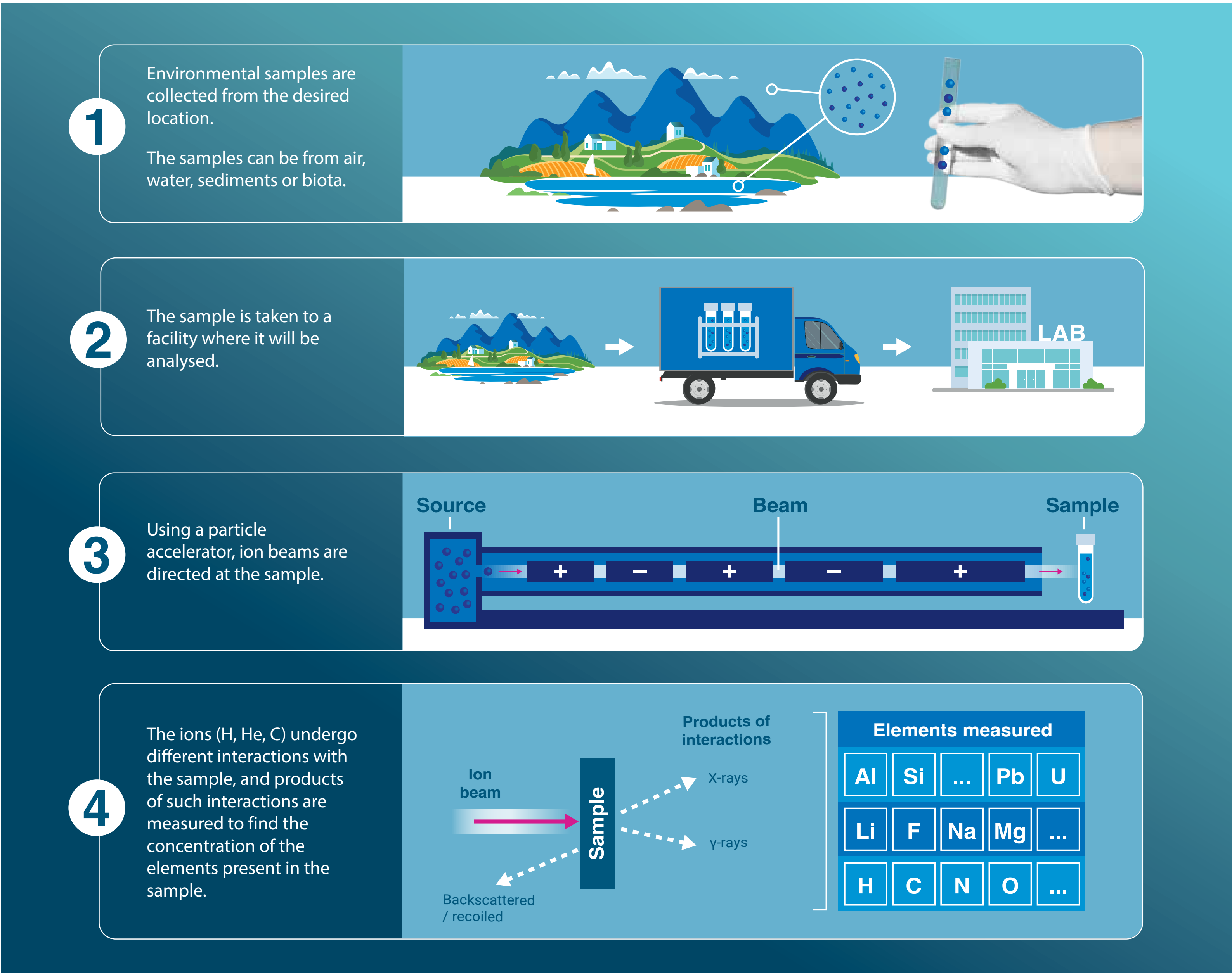
The accelerators most commonly used for the characterization of samples from environmental monitoring are electrostatic accelerators (see page 4).

Assessing air and water pollution is critical to addressing global health. Asia is home to over 60 per cent of the world's population and 13 of its largest cities. Air and water pollution are high on the agenda in the continent's largely urbanized areas. To help experts characterize air samples, the IAEA has been collaborating with 15 Asian countries to collect weekly samples of fine and coarse airborne particles, which impact the air breathed by over 110 million people. Between 2002 and 2017, accelerator-based ion beam techniques not only revealed the presence of many elements in collected samples but also helped to identify likely sources of air pollution.

In addition, electron beams, which are different from ion beams (see page 26), can be used to treat wastewater or plastics (see page 10). For example, the technique has a clear advantage over conventional water treatment technologies, such as chemical and biological treatments, because with electron beams, no chemical disinfectants are needed to kill microorganisms. In Hubei Province, China, there is a specialized treatment facility that uses electron beam technology to sterilize medical wastewater and decompose antibiotics. With the capacity to treat 30 million litres of industrial wastewater per day, it is the largest irradiation-based wastewater treatment facility in the world and was built on technology transferred by the IAEA. The treatment process saves 4.5 billion litres of fresh water annually — enough to quench the thirst of 100 000 people.

Meanwhile, synchrotrons, a special type of ring accelerator, are also used in environmental studies and help experts to analyse elements, map their distribution and determine their chemical species. By using X-rays as a probe, these complex accelerators can be deployed in mining and industrial processes, where traditional methods cannot provide sufficient data to predict likely environmental outcomes, bioavailability or the risks posed by contamination. In mining, for example, synchrotrons help predict future behaviour, such as the movement or dissolving of metals or minerals.

For more than seven years, the IAEA has operated jointly with Italy's Elettra Sincrotrone Trieste (EST) a multipurpose end station at the X-ray fluorescence (XRF) beamline, and developed new hardware and analytical methods. Through such collaborations, the IAEA supports and promotes synchrotron radiation-based research and training activities for research groups, especially in countries with limited experience and resources to access and use synchrotron radiation facilities. Such experiments have helped in the study of environmental issues in several countries, including fine aerosol atmospheric and indoor particles in Hungary and Jordan; the spatial distribution of lead in vegetation growing around mining environments in Spain; the distribution and chemical state of cadmium accumulated in oysters and scallops in Italy; titanium in agricultural soils amended with sludge from water treatment plants in Mexico; and the microscopic processes involved in reducing pollutants in mine-polluted Italian rivers.



(Graphics: A. Vargas Terrones/IAEA)

Ancient Roman archaeology resurfaces with nuclear science

By Michael Amdi Madsen

In 1996, Belgian diver René Wauters made the archaeological discovery of a lifetime. Exploring the 45-metre-deep waters of Vele Orjule, a Croatian islet in the Adriatic Sea, he discovered a mysterious ancient bronze statue. Researchers would carefully study the statue for more than a decade to determine its age, origin and even the methods of its construction, thanks to nuclear techniques.

Researchers used accelerator-based techniques to pin down Apoxyomenos's age, origin and methods of construction.
(Photo: Vassil /Wikimedia Commons)

Naked and muscular, Apoxyomenos represents a male athlete scraping sweat and dust from his body. When the largely corroded statue was pulled from the sea in 1999, a long desalination and restoration process commenced. Upon completion in 2005, archaeologists were left puzzled: Apoxyomenos's motif is not unique, so was this statue Roman or Greek? Pinning down its origins was impossible until 2009, when an accelerator helped to provide some clarity.

"Unraveling Apoxyomenos's past relied on several nuclear techniques to better understand its structure at the atomic level," said Lena Bassel, an associate project officer for heritage science at the IAEA. She works with experts from around the world in applying nuclear techniques for artefact characterization. Bassel points to a study published in the Journal of Archaeological Science in 2010 , where researchers, who had applied accelerator mass spectrometry to the organic material found inside Apoxyomenos, were able to carbon date the statue to between 100 BCE and 250 CE.

The researchers also applied accelerator-based micro-particle induced X-ray emission (PIXE) to determine the original composition of the alloy, and multi-collector inductively coupled plasma mass spectrometry to better understand the statue's lead isotope composition. Isotopes are specific forms of a chemical element that vary by atomic mass and physical properties. Scientists can look at the ratio of different lead isotopes in a sample and cross reference it with known properties of geographical areas to identify where the sample came from. "They used the accelerator analytical technique to pinpoint the origins of the statue's lead to the Eastern Alps or Sardinia, and concluded that the statue was a Roman copy of a Greek original," said Bassel.

Five years later, researchers examined Apoxyomenos again using a high lateral resolution PIXE technique. They found the inlaid lips of the statue to be a very pure unalloyed copper. X-ray radiography revealed how the inlays were inserted and fastened into position, as well as the sophisticated casting and joining techniques of the limbs. The researchers concluded that Apoxyomenos was very clearly a copy of a much older — mid fourth century BCE — statue, made through an indirect lost-wax process casting technique that used an alloy with a low lead composition.

"Accelerator-based techniques have an important role in the characterization of heritage objects, and Apoxyomenos shows us that an approach using several types of analyses is often needed. The IAEA is fostering these applications," said Bassel. Since 2018, the IAEA and its Members

States have promoted the use of Atoms for Heritage, and last year established a strategic partnership with the University of Paris-Saclay in France to enhance the use of nuclear techniques in characterizing and preserving cultural and natural heritage. In collaboration with the IAEA, the university will focus on scientific research and development, and on transferring knowledge to and best practices with experts from around the world.

Romans risen from the Rhône

Nuclear techniques in archaeology are not limited to characterization, and irradiation has for a long time played an important role in artefact preservation. Famously, the 3200-year-old mummy of Egyptian Pharaoh Ramses II was irradiated in 1977 to remove fungi and insects, but the technology has been in continuous use in many other projects since.

In 2004, less than four metres below the surface of the Rhône River in Arles, France, a Roman ship from the first century CE was discovered. Dubbed the 'Arles-Rhône 3', the 31-metre-long oak barge was probably sunk by a flash flood that covered it in a layer of fine clay.

"The clay helped preserve the boat and its valuable artefacts, but anaerobic bacteria dissolved the wood's cellulose, which was replaced with water. This posed a challenge in 2011 when researchers planned to raise the ship from the riverbed and install it in a museum, because, as it dried, the wood would collapse," said Laurent Cortella, a research engineer from ARC-Nucléart, a restoration and conservation workshop in Grenoble.

ARC-Nucléart came up with a solution: they bathed the wood in polyethylene glycol, freeze-dried it, and treated parts of the boat with irradiation. "Like drying glue with a hairdryer, restorers used irradiation to solidify the radio-curable resin and keep the wood's fibrous structure together," said Bum Soo Han, a radiation chemist at the IAEA who is working within the Atoms for Heritage framework to promote the use of irradiation technologies in cultural preservation.
Han offers technical support to cultural preservation efforts globally and sees demand for such applications growing.

"Arles-Rhône 3 can be visited today at the Departmental Museum of Ancient Arles, but you do not need to go to France to see artefact preservation by irradiation; such techniques are applied widely," said Han. In 2017, the IAEA released Uses of Ionizing Radiation for Tangible Cultural Heritage Conservation, a publication showcasing the successful application of these techniques around the world. Han is now working on the next edition of that IAEA series, focusing on good practices in the disinfection of cultural heritage artefacts and archives using ionizing radiation. It is expected to be published in 2023.

"Accelerator-based techniques have an important role in the characterization of heritage objects, and Apoxyomenos shows us that an approach using several types of analyses is often needed."

— Lena Bassel, Associate Project Officer for heritage science, IAEA

The ancient Roman ship, Arles-Rhône 3, has been preserved with nuclear techniques and is on display at the Departmental Museum of Ancient Arles, France.

(Photo: Cd13/MdDa/Chaland Arles Rhône 3 © Remi Benali)

Plastic pollution

Recycling with radiation to protect the environment

By Puja Daya

Over 5000 kilometres from the nearest major land mass, Henderson Island is perhaps the most isolated place on earth. Yet, despite a complete absence of people, this paradisical South Pacific island is awash with over four billion plastic pieces and particles. The litter lining Henderson's beaches is not only unsightly, but also deadly to the marine life that is choked or trapped by it. Plastic debris like this is just one example of the fate of over eight billion tonnes of plastic that have been produced since 1950.

The IAEA is working with experts from all over the world to change that fate and protect marine life and the environment from plastic pollution. With its partners, the IAEA is researching and developing ionizing radiation techniques to affordably reprocess and recycle plastics. These techniques involve using electron beam accelerators (see page 26) to irradiate post-consumer plastics to recycle them and to more easily reform them into other products.

The technique is promising because it is not entirely new and has a long and successful story. Irradiated polymers are found all around, from the rubber tyres on a car to hot water pipes and food packaging. "If we can use this technology in industrial applications to gain new features in plastics, there is nothing stopping us also using irradiation to reform and restructure plastic to improve its recyclability and reduce the amount of plastic disposed," said Celina Horak, Head of the Radioisotope Products and Radiation Technology Section at the IAEA.

Plastics are made up of different types of polymers — a substance made of long chains or networks of repeating groups of atoms called monomers. The irradiation of polymers produces different effects on the polymers that are beneficial for recycling, reducing and reusing plastic waste.

A new IAEA coordinated research project to develop the use of ionizing radiation in recycling polymer waste is spearheading research in this area. "Irradiating materials is no longer just a manufacturing tool, but also a recycling tool, so the ionizing radiation techniques used to modify polymers are relevant for plastic waste processing," said Bin Jeremiah Barba, Science Research Specialist at the Philippine Nuclear Research Institute. Her institute is just 1 of 18 countries, which are collaborating to consider how radiation processes such as cross-linking, chain scission, grafting and other surface modification can help countries to develop more affordable and accessible recycling methodologies.

Cross-linked polymers

The process of cross-linking refers to the use of electron beam irradiation to form bridges between polymer strands. By connecting polymer strands together, the properties of the material are enhanced, and can be used

Eight billion tonnes of plastic have been produced since 1950. Much of it lies unrecycled in dumps, in the ocean or on beaches.
(Photo: M. Gaspar/IAEA)

to create longer lasting, more resistant, better quality products. This is common practice in the creation of vehicle tyres, as it allows manufacturers to reduce the size and thickness of the rubber — reducing raw material and production costs, and making the product more sustainable.

Degrading polymers

Irradiation is used in almost the opposite way through chain scission — a process in which polymers are cut up or ‘degraded’. “This process makes materials more brittle and easier to be ground into finer polymers. For example, polytetrafluoroethylene, a chemical coating more commonly known by its brand name, Teflon, is degraded and then used in motor oil lubricants and additives for inks,” said Olgun Güven, a radiation polymer expert at Hacettepe University who is leading efforts in Turkey. Under the coordinated research project, experts are considering how chain scission can be used in chemical recycling, in which a product is broken down into its basic chemical form to generate new raw materials or fuel. Chain scission for recycling could massively enhance the production of new products from single use polymers, he said.

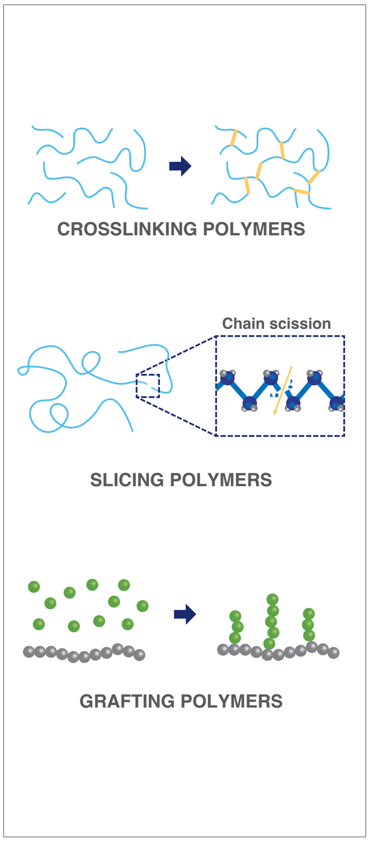
Grafting polymers

Grafting is the process of growing a tailored short polymeric chain on the surface of another polymer in order to modify its properties. The same technique can be used to combine polymers that would typically be incompatible together, for the easier remoulding and restructuring of waste.

These techniques are just a few ways in which the IAEA is exploring the use of ionizing radiation for recycling waste from plastic. “The very tools used in industry can be applied to recycling and are an affordable and accessible part of the solution to reduce the plastic waste harming our environment,” said Horak. She said that the ongoing coordinated research project will improve and validate this plastic recycling technology and help determine its feasibility for use in countries. It will also develop a plan for transferring the knowledge and turning it into action.

To improve capabilities worldwide in the application of innovative radiation techniques for reducing plastic waste by recycling it, the IAEA launched the Nuclear Technology for Controlling Plastic Pollution (NUTEC Plastics) initiative in 2021. The initiative is dedicated to helping countries use various nuclear techniques. It provides science-based evidence to characterize and assess marine microplastic pollution, while also demonstrating the use of ionizing radiation in plastic recycling, transforming plastic waste into reusable resources.

NUTEC Plastics involves coordinated research projects that help to provide precise scientific data to inform plastic pollution policies, strengthen methodology to track plastics and improve the scalability of the recycling technology. IAEA technical cooperation projects in the initiative offer researchers equipment and training to transfer knowledge and facilitate plastic recycling projects. The development of guidelines will help countries set up and establish facilities to use nuclear techniques to tackle plastic pollution.



Streamlining food pest control through irradiation

By Joanne Liou

There is more than meets the eye when it comes to the spices, seeds, fruits and vegetables that travel from distant origins to your local grocer. A small dose of radiation helps make it possible for food products to stay fresh and last the journey without spreading invasive organisms.

The IAEA, in partnership with the Food and Agriculture Organization of the United Nations (FAO), is supporting the latest developments in the fields of food and phytosanitary irradiation, in order to help streamline the pest control process and facilitate international trade. Food and phytosanitary irradiation are post-harvest treatments that use ionizing radiation produced by a source, such as cobalt-60, or generated by accelerators.

"Ionizing radiation is gentle on food, but not on microbes or invasive pests, and it enables international trade," said Carl Blackburn, Food Irradiation Specialist at the Joint FAO/IAEA Centre of Nuclear Techniques in Food and Agriculture.

In-house irradiation devices

Before being shipped to their final destination, certain food products are first prepared or collected from their place of origin, packaged, and then taken to an irradiation facility. These facilities often rely on cobalt-60 as the source of ionizing radiation. "Colbalt-60 is easy to use for gamma rays, but it might be challenging to procure and transport," Blackburn said. "The IAEA has been encouraging a new streamlined approach, bringing irradiation in-house with soft radiation, like low energy electron beams (LEEBs) and low energy X-rays, where the irradiator can be placed inside a food factory or packing house."

In 2021, an IAEA coordinated research project demonstrated the feasibility of using LEEBs and soft X-rays to reduce infestation and microbial contamination. "This means that low energy electron beams, or soft electrons, can be applied as a surface treatment, and they do not affect qualitative properties," said Setsuko Todoriki, a project

Irradiation helps make it possible for food products, like strawberries, to stay fresh and last long journeys.
(Photo: R. Mithare/Unsplash)

participant and Research Lead at the National Agriculture and Food Research Organization in Japan. "Because of the significantly lower energy in comparison to conventional electron beams, low energy electron beams could be implemented into the processing line and operated on site." The project developed dosimetry methods for soft X-rays. A new and ongoing coordinated research project devoted to low energy beam treatments is further developing and promoting the innovation of in-house radiation processing of foods, including the development of dosimetry tools and techniques for LEEBs for specific foods, in collaboration with food industry partners.

Developing generic treatments

Over the past 15 years, the volume of commodities irradiated for phytosanitation has increased significantly to nearly 100 000 tonnes per year globally. However, traded irradiated food products are only a slim fraction of those treated by other phytosanitary measures. The volume of mangoes that undergo hot water treatment in Mexico alone, for example, amounts to about 300 000 tonnes per year, explained Guy Hallman, a phytosanitation expert based in the United States of America. "Phytosanitary irradiation has advantages over other phytosanitary treatments, such as cold, heat and fumigation, which may alter the taste or texture of foods," Hallman said. Having more internationally accepted standards for irradiation could support the further uptake of this treatment option and increase trade, he added.

The International Plant Protection Convention (IPPC), a multilateral treaty administered by the FAO, establishes standards to prevent and control the spread of pests. Blackburn said that these standards are the bedrock of all bilateral trade agreements for treated fruit and vegetables, but irradiation treatment standards only cite radiation doses that are species specific. Just 2 out of the 19 irradiation treatments recognized by the IPPC are generic treatments that prevent fruit flies from being able to spread through trade in fresh produce and reproduce in new locations where they could devastate farming and the environment.

In February 2022, the IAEA launched a coordinated research project to address this and develop at least five generic phytosanitary irradiation treatments for adoption by the IPPC to boost the commercial use of phytosanitary irradiation. These new generic irradiation treatments could potentially address more than 90 per cent of the quarantine issues encountered by traded fruits and vegetables, Blackburn said.

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— Carl Blackburn, Food Irradiation Specialist, Joint FAO/IAEA Centre of Nuclear Techniques in Food and Agriculture.

Radiation to sterilize healthcare products

Beyond the sanitary, food quality and phytosanitary uses, much higher dosage radiation technology has been used to sterilize health care products since the 1950s. Radiation treatment is part of the manufacturing process for nearly half of all single-use products in the medical field, such as bandages, gloves, gowns, face masks, syringes and other equipment. Radiation sterilization destroys contaminating microorganisms, while preserving the properties and characteristics of the product.

"Almost 50 per cent of medical products are being sterilized by radiation technologies — gamma, electron beam and X-rays — and it is a growing trend," said Celina Horak, Head of the Radioisotope Products and Radiation Technology Section at the IAEA. "Additionally, ionizing radiation has been an effective and established tool for sterilizing personal protective equipment (PPE), which has been in high demand during the COVID-19 pandemic."

In 2020, following the onset of the pandemic, the IAEA studied the feasibility of sterilizing used medical equipment with ionizing radiation. The study concluded that there is potential to reuse irradiated medical protective clothing, except for respiratory face masks such as N95 and FFP2 masks. The study found that used masks that had been irradiated "showed a significant decrease in filtration efficiency in the submicronic domain." This decrease is likely due to changes in the electrostatic properties of the filter caused by irradiation.

Neutrons for neurons and cyclotrons for radioisotopes

By Michael Amdi Madsen

"Firing neutrons at boron atoms in certain brain, head and neck cancers can save lives."

— Ian Swainson, Nuclear Physicist, IAEA

Glioblastoma is an aggressive malignancy and accounts for about 15 per cent of all brain tumours. Even when initially controlled by treatment, the cancer almost always returns. Surgery and radiotherapy can extend survival by some months, but the brain cancer usually ends life within one to two years of diagnosis, and less than five per cent of people survive longer than five years. As with glioblastoma, many cranial cancers, are a challenge to treat due to the sensitive nature of normal brain tissue to surgery and radiotherapy, but there is hope that could change soon, thanks in part to new therapies made possible by accelerators producing intense sources of neutrons.

"When you think of performing nuclear reactions, you probably don't imagine a human head is the best place to do it — but you'd be wrong," said Ian Swainson, a nuclear physicist at the IAEA. He is helping develop IAEA guidance on accelerator applications for neutron production, including in medicine. He said using this technology in one cancer therapy in particular, boron neutron capture therapy (BNCT), is very promising: "Firing neutrons at boron atoms in certain brain, head and neck cancers can save lives."

BNCT uses the destructive power that neutrons can unleash and relies on localizing damage to the tumour as much as possible. Harnessing neutrons' destructive ability is possible with boron-10 isotopes. "Boron-10 is non-radioactive and great at capturing neutrons. As a result, in a very localized nuclear reaction, boron breaks into two energetic fragments. So, by injecting a patient with special drugs that deliver boron-10 to tumour sites, we're putting a big bullseye on the cancer," Swainson explained.

Still largely experimental, BNCT is not widely available, but that is changing. In 2020, two BNCT facilities began clinical treatments in Koriyama and Osaka in Japan. In the same year, the IAEA and Japan's Okayama University agreed to enhance cooperation in BNCT through events, knowledge and information exchange, and the development of a BNCT facilities database.

"BNCT is a cutting-edge cancer therapy," Hirofumi Makino, President of Okayama University, said at the time. "It is a happy marriage of modern nuclear physics and up-to-date pharmaceutical cell biology. However, we should not forget the long history of struggle in developing this difficult medical technology."

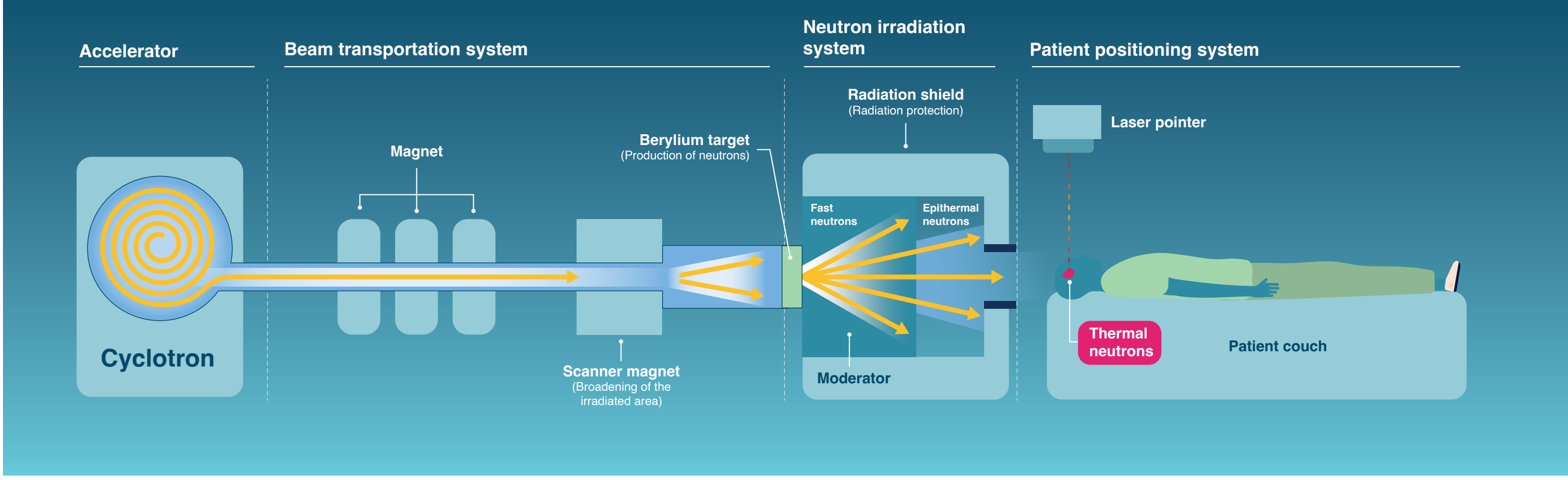
In 2001, the IAEA produced a technical report on BNCT, which became a reference work for the field. At that time, the only neutron sources involved were research reactors. Since then, a new generation of compact accelerator-based neutron sources has been developed, which can be installed directly in clinics. This has led to a major resurgence in interest in BNCT.

BNCT projects are also being pursued in Argentina, China, Finland and the Republic of Korea. "20 years ago, using neutrons from accelerators in cancer treatment was just theory. Now it's reality and we're reflecting this development in an upcoming technical document entitled Advances in Boron Neutron Capture Therapy," said Swainson.

The cyclotron revolution

Determining the feasibility of BNCT in a patient requires injecting a boron compound radiolabelled with fluorine-18 (^{18}F), produced with cyclotrons, followed by imaging the patient using a nuclear medicine technique called positron emission tomography–computed tomography (PET–CT). The ^{18}F labelled compound is called 4-borono-2-^{18}F-fluoro-phenylalanine, or FBPA.

A representation of the clinically approved BNCT system in Japan



(Graphics: A. Vargas Terrones/IAEA)

"FBPA is important because it confirms to doctors that a tumour has absorbed a boron containing compound and is ready for BNCT. Without it, the therapy may not work. As BNCT becomes more widely available, we're going to need cyclotrons to meet FBPA demand," said Amirreza Jalilian, a radioisotope and radiopharmaceutical chemist at the IAEA. A cyclotron is a type of particle accelerator that produces radioisotopes used in nuclear medicine by firing a particle beam at stable isotopes. The interaction results in a nuclear reaction that creates short-lived radioisotopes. Because these radioisotopes decay quickly, they need to be produced near or on the site where treatment takes place and used right away.

Jalilian notes that, although the number of research reactors used in the production of radioisotopes is rather stable, new, versatile and increasingly affordable cyclotrons are on the rise worldwide. Many of the short-lived radioisotopes used in patients can be produced by cyclotrons in hospitals, and that is a major advantage for the technology.

The radiopharmaceutical fluorodeoxyglucose is just one example. It relies on ^{18}F, which can be produced with cyclotrons. That radiotracer is used in around 95 per cent of PET–CT procedures, and so is critical in neuroimaging and diagnosing cancer.

Another workhorse among radiopharmaceuticals is gallium-68 (^{68}Ga), which is the key component of some theranostic radiopharmaceuticals — a type of pharmaceutical that uses radioisotopes both for diagnosis and therapy through the release of radiation. Such radiopharmaceuticals play an important role in diagnosing and following up on cancers, and shows particular promise in addressing prostate cancer. Producing ^{68}Ga, however, does have its challenges.

"Today, the most common method for producing ^{68}Ga is with a non-accelerator system called a generator, but generators simply cannot produce enough to meet demand. Cyclotrons offer an effective alternative means of direct production and are already greatly expanding the availability of ^{68}Ga," said Jalilian, explaining that ten centres around the world are now routinely using cyclotrons to produce ^{68}Ga. The IAEA is currently coordinating a research project to support the exchange of international expertise in cyclotron-based production of ^{68}Ga, and in 2019 released Gallium-68 Cyclotron Production, a publication dedicated to the topic.

Truth-revealing atoms

Accelerator-based analytical techniques detect art forgeries

By Joanne Liou

The story behind a painting typically starts with identifying the artist and when the work was produced. And truth be told, there are some allegedly prized paintings that tell a story of criminal deception. Art forgery can be lucrative and go undetected, but analysis techniques, including radiocarbon dating using accelerator mass spectrometry (AMS), can reveal the fakes.

"Nuclear analytical techniques are extremely powerful in determining the composition, origin, authenticity and age of samples or objects, and hence have direct relevance to forensic science."

— Aliz Simon, Nuclear Physicist, IAEA

"Nuclear analytical techniques are extremely powerful in determining the composition, origin, authenticity and age of samples or objects, and hence have direct relevance to forensic science," said Aliz Simon, a nuclear physicist at the IAEA. "In this context, nuclear techniques may be effective tools for a variety of purposes, such as the investigation of art forgery, detecting illicit trade, identifying counterfeited food and sub-standard medicines, and trace evidence analysis, for example, pieces of glass from a crime scene."

Forensic science is the application of scientific methods or expertise to examine evidence to assist in criminal investigations. It comprises an array of disciplines, from DNA and fingerprint analyses to compositional and glass analyses. In the field of forensics, accelerators are used to analyse a material's composition, structure, age and other properties. "X-rays, neutrons and ions offer advantages over conventional methods," Simon said. "They can analyse one particle among millions and pinpoint origin with great accuracy, while leaving evidence intact."

Radiocarbon dating

All living things, including a painting's canvas (made of natural fibres) or frame (made of wood), absorb carbon from the atmosphere, including carbon-14. Carbon-14 is an unstable isotope that decays at a known rate. When plants or animals die, they cease to absorb carbon, and the radioactive carbon already accumulated decays. The age of material can be determined by the amount of carbon-14 present, using AMS to measure the ratio of carbon isotopes. This technique, known as radiocarbon dating, is widely used to date fossils and, more recently, has been applied to date suspected art forgeries. "Radiocarbon dating of canvas provides the earliest date an artwork could have been produced because of the time between harvesting linen for canvas and the actual painting of the piece," said Lucile Beck, manager of the Carbon-14 Measurement Laboratory at France's University of Paris-Saclay.

The amount of carbon-14 in the atmosphere has fluctuated in recent history, specifically from the mid-1940s and 1950s because of nuclear weapons tests. Carbon-14 concentration in the atmosphere peaked around 1964 and has declined since. "We can easily identify materials containing modern weapons-derived radiocarbon because their level of carbon-14 concentrations is higher than pre-1950s levels," Beck said.

During a 2019 investigation of potential forgeries by France's Central Office for the Fight against Illegal Trafficking in Cultural Goods, Beck tested two paintings from a collection thought to have originated from the late 19th and early 20th centuries. Researchers collected samples of fibre from the canvases and reduced them to about one milligram of carbon that was then measured with AMS.

“With AMS radiocarbon dating, we were able to prove that the two paintings — one Impressionist and one Pointillist — were forgeries,” Beck concluded. “Based on the excess of carbon-14 detected in the fibres, the paintings had not been painted at the beginning of the 20th century by the alleged artists, who died in the 1940s. The content of the fibres revealed the canvases were manufactured in the mid-1950s or, more likely, after 2000.” The measured carbon-14 levels corresponded to levels before and after levels peaked in the 1960s.

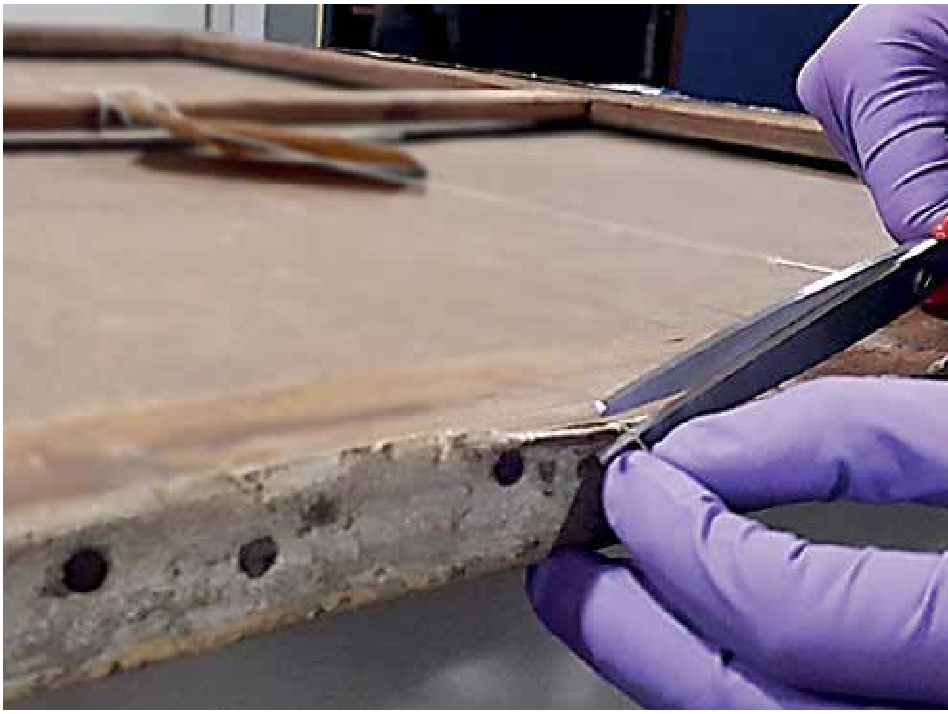
Accelerating nuclear for forensic science

In 2017, the IAEA embarked on a four-year coordinated research project to enhance nuclear analytical techniques to meet the needs of forensic science. The project focused on three main areas: glass analysis, food authentication and cultural heritage, including the investigation of art forgery. Project participants were from Brazil, Croatia, Finland, France, Hungary, India, Israel, Italy, Jamaica, Portugal, Singapore, Slovenia, Switzerland and Viet Nam. Some results of the project, that range from the analysis of coffee to windshield glass samples, as well as the art forgery study in France, are already published in a special issue of the journal Forensic Science International.

Under the framework of the project, in 2019, the IAEA jointly hosted a workshop with the Abdus Salam International Centre for Theoretical Physics in Trieste, Italy. It highlighted how accelerator-based techniques can complement standard forensics methods in criminal investigations. Concurrently, the IAEA also launched an e-learning course on nuclear analytical techniques for forensic science.

Building upon the success of the project, the IAEA signed a Memorandum of Understanding with the United Nations Interregional Crime and Justice Research Institute (UNICRI) in 2021 to boost cooperation in preventing and countering criminal activities through nuclear science and technology.

As a next step, the IAEA plans to launch a follow-up coordinated research project focused on detecting the illicit trade of heritage objects and illicit mining of precious metals.



A fibre of an alleged impressionist painting is removed from the canvas to test whether the piece is a forgery.
(Photo: L. Beck/University of Paris-Saclay)

Quantum modification

Utilizing accelerators to implant single atoms for biosensing

By Joanne Liou

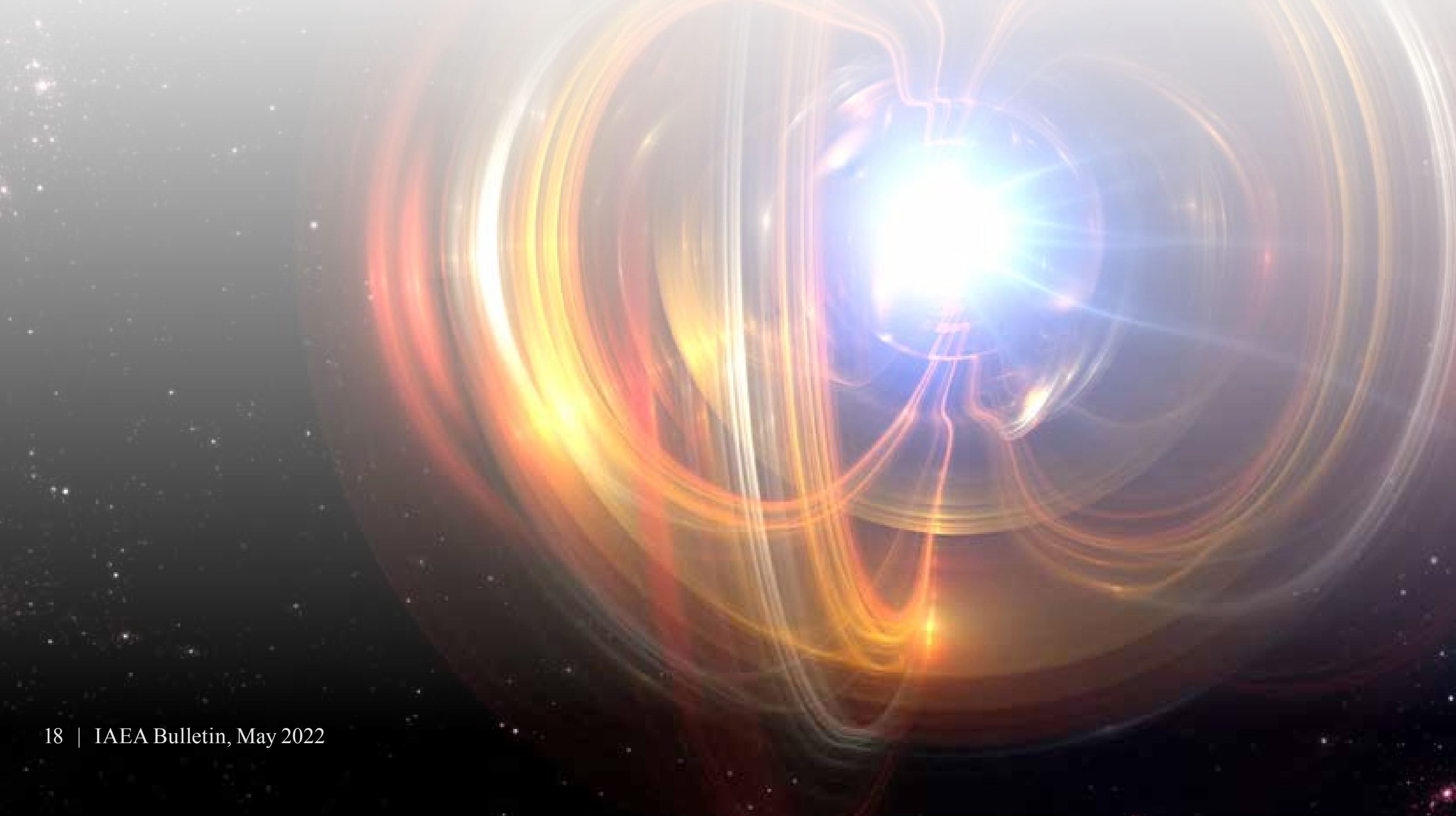
In the field of quantum technology, accelerators have been intensively applied within the last decade to modify and characterize materials. Accelerator-based techniques use high-energy ions to alter atomic structures in materials, which allows scientists to control the behaviour of single atoms. The main use of accelerators has been in ion implantation, which is a widely used technique in the semiconductor industry and has been around for decades.

"For semiconductors, a high number of ions are implanted to change the electrical properties of, for example, silicon," explained Andrew Bettiol, Associate Professor at the National University of Singapore. "For quantum technologies, we have a very different aim. We want to control the ions at the single ion level. We are not implanting millions or billions of ions; we are implanting exactly one ion."

The challenge in single ion implantation is determining when, where and if, in fact, a single ion is implanted. "And just because you implant the ion into the material, it doesn't mean it works the way it should as a qubit or colour centre," Bettiol said. Qubits, or quantum bits, are complex versions of the information-carrying bits used in conventional computing, and colour centres are defects that emit light for quantum sensing.

In May 2021, the IAEA hosted a four-day training workshop on materials engineering using ion beams. The workshop included an introduction to focused ion beam instrumentation and the detection of single ions. More than 80 participants, half of them from developing countries, attended the virtual workshop, which was implemented under a coordinated research project and aimed to improve understanding of and engage newcomers to the quantum field. The workshop also coincided with the launch of an IAEA e-learning course, Ion-beam Engineering of Materials for Quantum Technologies, which aims to engage the next generation of quantum experts.

"The IAEA has been at the forefront of coordinating international collaboration, research and development in quantum



A new IAEA project will foster the development and optimization of a biosensor platform that would allow the exploration of sub-cellular mechanisms.
(Photo: Adobe Stock)

technologies aligned with national and international initiatives," said Aliz Simon, a nuclear physicist working on accelerators at the IAEA. "The IAEA is continuing its efforts in coordinated research to realize the benefits of quantum for the greater good of society." A new IAEA project, expected to be launched later this year, will foster the development and optimization of a biosensor platform based on colour centres in a diamond, which would allow the exploration of sub-cellular mechanisms. In the quantum field, diamonds are used as semiconductors to consequently sense electric and magnetic fields in single living cells.

Colour centres for quantum sensing

Diamond, in its purest form, is a lattice of carbon atoms that has more than 500 documented defects that emit light. One of these known defects is the nitrogen–vacancy (NV) colour centre. An NV colour centre occurs when one carbon atom is taken away to create a vacancy, and a neighbouring carbon atom is replaced by a nitrogen atom. "NV colour centres can naturally occur and are randomly distributed. With accelerators, we can artificially create this defect with ion implantation and create them in specific regions within nano-scale diamond crystals," Bettiol said. Among the known defects of diamond, the NV centre can be embedded in nano-scale diamond crystals, and it can be controlled at room temperature and is biocompatible — not harmful or toxic to living systems.

Diamond NV centres have the capability of magnetic field sensing through a technique called optically detected magnetic resonance, or ODMR. The ability to image magnetic fields has implications in both biology and materials science. "It's an optical way of looking at light emission and detecting very tiny magnetic fields that occur in biological processes," Bettiol explained. "This quantum biosensing technique could be applied to visualize or measure processes that work at the cellular level and have a very small magnetic field, such as the magnetic fields that are produced when neurons fire in our brains."

Bettiol's current research applies the ODMR technique to detect malaria. "Red blood cells that have been infected with malaria have tiny magnetic particles that can be detected with ODMR," he said. "Anything that produces an electromagnetic field could potentially be detected using this method."

The upcoming IAEA project will further investigate quantum sensing using ODMR, as well as the characterization and optimization of sensing devices. The new project, which will bring together researchers who have a common interest in biosensing, stems from a previous project that was broader in scope and aimed at advancing accelerator-based ion beam tools. "The IAEA is a good vehicle for collaboration and has created a community for experts to exchange information and learn from one another," Bettiol said.

> **"This quantum biosensing technique could be applied to visualize or measure processes that work at the cellular level and have a very small magnetic field, such as the magnetic fields that are produced when neurons fire in our brains."**
>
> *— Andrew Bettiol, Associate Professor, National University of Singapore*

Nuclear techniques for the development of advanced materials

By Anass Tarhi

From active food packaging based on nanocomposites loaded with essential oils, to radiation-grafted super-absorbent polymers, radiation-processed advanced materials play an increasingly important role in reducing food waste, enhancing agricultural performance, improving health care and much more.

In addition to their light weight and easy fabrication, advanced materials modified using nuclear techniques offer enhanced performance and durability. Radiation technologies, including accelerators, have strengthened their place and, through many applications, contribute to sustainable development.

Uses of advanced materials

To create advanced materials or improve the production of high-performance materials, several radiation-assisted processes are now well established and implemented in industry. For example, the increased suitability of plastics or rubbers exposed to radiation enables the production of various materials, such as plastic tubes resistant to heat and pressure used for circulating water and heating fluids in buildings.

"High-performance materials produced with radiation can be found everywhere and in everything," said Celina Horak, Head of the Radioisotope Products and Radiation Technology Section at the IAEA. "They are found in everyday objects that have been made stronger and safer. Some of these materials are even used in making your lifestyle more sustainable."

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Radiation processing is also applied to dry or harden solvent-free paints, inks and coatings, and to improve the strength, temperature resistance and impermeability of bio-based and biodegradable packaging materials. Porous ceramics with silver nanoparticles generated in situ are now used in various countries for water purification in rural communities.

Benefits of advanced materials in the context of climate change

Meeting growing energy demand while addressing climate change requires further developments in renewable energy production, storage and recycling. "Radiation technologies are well suited to fabricate task-specific membranes and bulk composites for fuel cell technology, to produce more efficiently renewable energy," said Xavier Coqueret, a professor at the University of Reims Champagne-Ardenne. He said radiation pre-treatment can be used to improve lignocellulosic biomass or the

conversion of sunlight energy through advanced photovoltaics.

To address another environmental issue, the global plastic waste burden, Coqueret said efficient recycling methods using radiation are needed in the design of advanced plastic and composite products that would otherwise not be reusable with conventional methods (see page 10).

Radiation effects on advanced materials

Strong, resilient and durable materials are critical in industry in general but are particularly important in the nuclear sector, where the safety of reactors and the feasibility of fuel cycle operations depend on the materials used. For materials in nuclear reactors, the two biggest challenges are heat — addressed by cooling systems — and radiation.

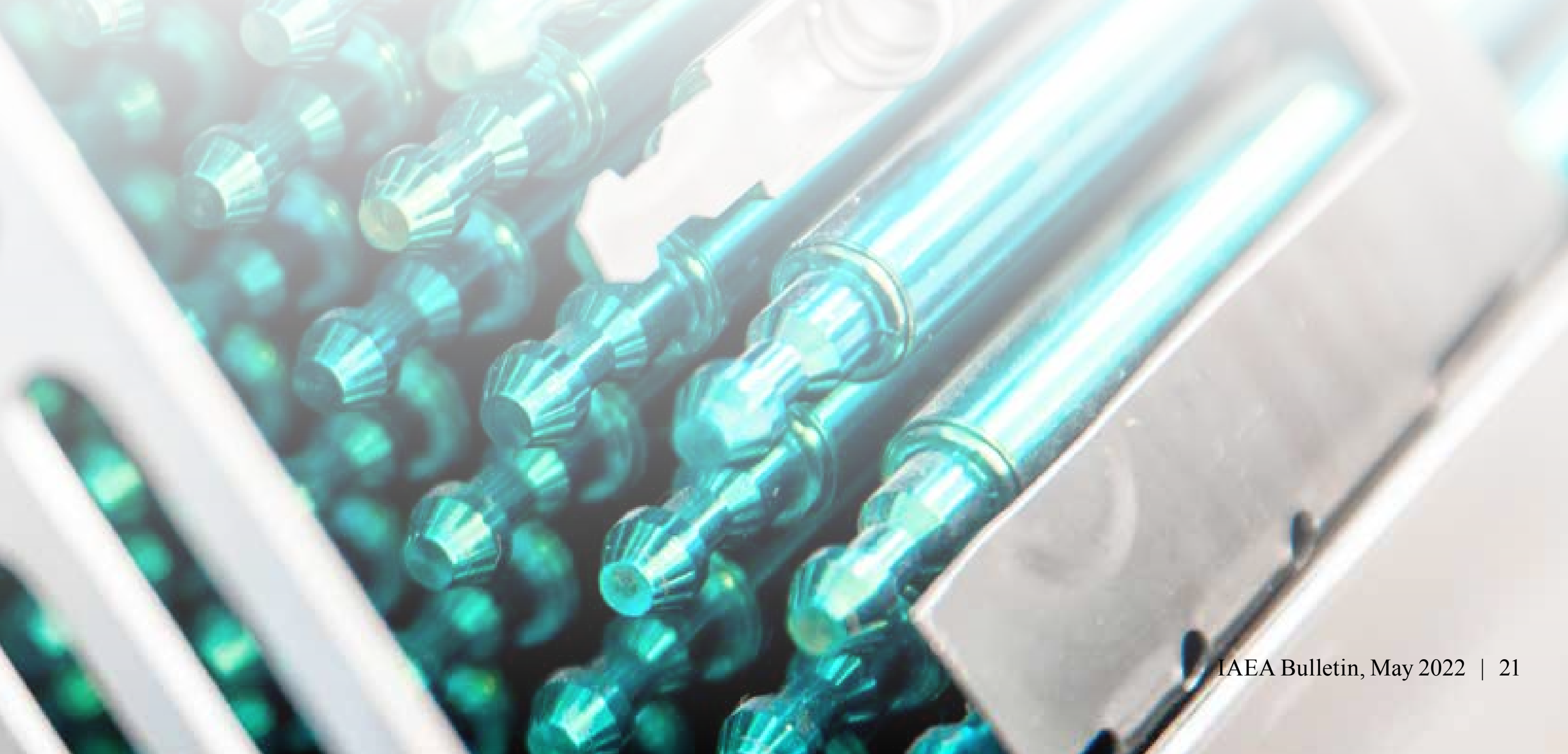
“Structural materials inside nuclear reactors are subjected to damage from fast neutrons that knock atoms out of position and create hydrogen or helium in the form of gas. This can ultimately lead to swelling, the creation of voids, and various other structural and mechanical changes that limit their ultimate lifetime in service,” said Ian Swainson, a nuclear physicist at the IAEA. “Testing materials against radiation is therefore essential, and accelerators can help make testing more widely available.”

Charged particles lose most of their energy towards the end of their journey through materials, causing significant but localized damage. For this reason, researchers plan to test candidate materials for future nuclear reactors using charged particles from ion beam accelerators.

“Testing materials with an accelerator is faster than using a reactor,” said Swainson, explaining that what can be completed in a day with an accelerator can take a year with a high flux test reactor. Typically, samples do not become radioactive, and damaged areas can be carefully sectioned and examined with microscopic techniques.

In 2016, Swainson helped organize a five-year-long IAEA coordinated research project in which samples of the same material were distributed to multiple accelerator facilities for irradiation, under identical conditions, and the BOR-60 fast research reactor in the Russian Federation for comparison. The post-irradiation analysis will contribute to improving site-to-site reproducibility among accelerator facilities and shed light on how well accelerators screen out poorly performing materials.

In August 2022, the IAEA will hold its Second International Conference on Applications of Radiation Science and Technology (ICARST-2022) to explore these issues and highlight applications and ionizing radiation developments. The conference, among other topics, will focus on advances and current technological or economical limitations in specific areas of advanced materials, and will help review achievements in well-established radiation processes for improved materials performance.



Rod elements used in nuclear reactors are made of advanced materials and must be resilient to heat and radiation.

(Photo: Adobe Stock)

Establishing ionizing radiation facilities in the Philippines and beyond

By Puja Daya

Cancer is the Philippines' second biggest killer, according to the 2020 Global Cancer Observatory, as the country suffers almost 100 000 cancer related deaths per year. Paramount to reducing this toll is early tumour detection, but with medical imaging scans costing, on average, close to US $2000, many Filipino people cannot even afford one.

"A major problem faced in the Philippines is the lack of resources to develop and maintain cancer detection. This is causing many cancer patients to be undiagnosed and untreated," said Carlos Arcilla, Director of the Philippine Nuclear Research Institute. Arcilla and his team hope to address this capacity shortage by establishing a new cyclotron — a type of ionizing radiation facility — in Manila, in order to produce radiopharmaceuticals critical for diagnosing and treating cancer, as well as brain and cardiovascular diseases.

Currently, the Philippines only has four cyclotrons, but they are privately owned, and the country's limited positron emission tomography–computed tomography (PET–CT) scanning facilities mean that just five per cent of cancer patients can receive cancer diagnoses. Cyclotrons are accelerators that produce radiopharmaceuticals, which are given to patients before receiving a PET–CT scan — a medical scan that creates high-quality 3D images, usually of organs and tissues, to help detect diseases and visualize tumours. With a new cyclotron, the Philippines can produce more radiopharmaceuticals domestically for improved access to PET–CT scanning.

Hosting a publicly owned cyclotron and PET–CT scanner, the new Nuclear Medicine Research and Innovation Center will enable, approximately, an additional 5000 patients per year to have access to accurate cancer staging.

"We aim to produce radiopharmaceuticals for both the Center and the neighbouring Philippine General Hospital in Diliman, allowing us to serve more patients and act as a tool for cancer research," said Arcilla. He said that the Center will also be a training hub in the region, so both the Philippines and neighbouring countries can become self-reliant in the production and use of radiopharmaceuticals.

The benefits of new ionizing radiation facilities

Radioisotopes and particle beams produced at ionization radiation facilities, such as cyclotrons, synchrotrons and other types of accelerators, are applied in medicine and health care, water security, food and agriculture, research, energy production, industrial and consumer products, forensic investigations, in the preservation of cultural heritage.

The synchrotron at Suranaree University of Technology, Thailand is applied in agriculture, medicine, pharmacy and industry.
(Photo: Synchrotron Light Research Institute)

Establishing more accelerator-based facilities around the world will lead to better and cheaper access to such benefits. Thus, alongside the Philippines, new facilities are being established in Argentina, Malaysia and Thailand — all with IAEA support.

Globally, demand for such ionizing radiation facilities is growing, and to better help countries meet it, the IAEA plans to release its Guidance for the Establishment of Ionizing Radiation Facilities this year. "Those involved in the development of ionizing radiation facilities can benefit from having guidance that will enable them to undertake the project in a well organized manner, enabling successful progress in its implementation, and full utilization after the facility begins operation and the provision of services. The publication will do just this by consolidating expert advice on establishing new facilities and improving existing ones," said Nuno Pessoa Barradas, the research reactor specialist at the IAEA responsible for the publication.

Ionizing radiation facilities can contain different types of equipment for the purpose of ionization. In Thailand, the Synchrotron Light Research Institute is planning to build a second synchrotron. The country's first (see image) has been running for 20 years and has helped Thai experts to sustainably use ionizing radiation to preserve cultural heritage artefacts (see page 8), lead forensic investigations (see page 16), and contribute to research and development.

"The current machine has made a significant impact in the country," said Supargorn Rugmai, Assistant Director for Academic Affairs and Head of the Research Facility Division at the Synchrotron Light Research Institute. "At the start, there was a lack of knowledge, but after setting up training programmes within the region, we are becoming experts. With the new facility, we will be able to make a greater social impact and apply the technology more widely."

Synchrotron light sources help to build and advance industrial, medical and basic research. The new synchrotron in Thailand will possess 2.5 times more energy than the old synchrotron. It will be used to advance scientific research and will improve the country's economy through the utilization of its high intensity X-rays in industrial product improvement and innovation.

Experts in Argentina and Malaysia are also developing new electron beam accelerator facilities. These will enable a larger production of radioisotopes for medical diagnoses and therapy, as well as advancing research and technology within the countries.

Through its technical cooperation programme, the IAEA is sending experts to Argentina, Malaysia, the Philippines, Thailand and other countries to help safely establish and maintain ionizing radiation facilities by training local experts so that they can independently run and maintain these facilities. In addition to this support, the IAEA publishes safety standards, provides virtual sessions and hosts an e-learning platform that about the Accelerator Knowledge Portal — a site for and by the accelerator community that provides training materials, information on accelerators around the world, and much more.

"Those involved in the development of ionizing radiation facilities can benefit from having guidance that will enable them to undertake the project in a well organized manner, enabling successful progress in its implementation, and full utilization after the facility begins operation and the provision of services."

— Nuno Pessoa Barradas, Research Reactor Specialist, IAEA

Enabling the safe, secure and peaceful use of irradiation facilities through law

By Anthony Wetherall and Chenchen Liang

Safe, secure and peaceful nuclear technology promises significant benefits to society, but the ionizing radiation essential to so many applications can pose significant risks to people's health and to the environment. Well-structured legal arrangements are required to assess, manage and control this radiation to minimize such risks.

"Experience shows us that nuclear law-making is not always an easy task. The three broad technical areas — safety, security, and safeguards — all need to be addressed in an adequate and comprehensive manner."

— Wolfram Tonhauser, Head, Nuclear and Treaty Law Section, IAEA

Ionizing radiation facilities (IRFs), important in many areas that involve nuclear technology (see page 22), do not pose radiation risks comparable to nuclear power plants and so are not subject to the same radiological safety and nuclear security requirements as reactors. IRFs and their related activities must be subject to standards of safety consistent with a graded approach. That is, they must be licensed, regulated, and inspected by regulatory bodies.

States have the fundamental responsibility of establishing, maintaining and strengthening comprehensive national legal frameworks, including regulatory frameworks. In many countries, the legal hierarchy is such that at the top level there are constitutional instruments, followed by a legislative framework at the statutory level, comprising of enactments of laws.

This framework provides the legal basis for implementing legally binding and non-binding international instruments such as the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management and the Code of Conduct on the Safety and Security of Radioactive Sources, as well as relevant IAEA safety standards and nuclear security guidance.

The legislative framework is the foundation for a system of regulatory control and provides for the establishment or designation of a regulatory body with the requisite independence, human and financial resources, and a clearly defined set of functions. This includes standard setting, authorization, inspection and enforcement, as well as the clear delineation and coordination of responsibilities. This legislative framework is essential for the safe, secure and peaceful use of ionizing radiation and countries look to IAEA support in establishing one.

Not always easy law-making

Over the years, national governments have sought assistance to establish or strengthen their national legal frameworks for nuclear technology. "Experience shows us that nuclear law-making is not always an easy task," said Wolfram Tonhauser, Head of the Nuclear and Treaty Law Section at the IAEA. "The three broad technical areas — safety, security, and safeguards — all need to be addressed in an adequate and comprehensive manner."

Additionally, national nuclear law must comply with the constitutional and institutional requirements of each country's legal system, while pursuing the greatest possible degree of harmonization and consistency among the legislative frameworks of other countries in the nuclear field.

Importantly, policy and decision makers need to recognize the special character of nuclear technology and its applications, not least since it can entail political, sensitive and strategic matters, as well as security risks of national, international and regional concern. In addition, lawmakers need to appreciate the cross-sectoral dimension of nuclear technologies and related facilities and activities, since they can be encountered in multiple sectors and areas, such as health, energy, industry, transport, water, food and agriculture.

As such, law-making gives rise to the need for comprehensive assessments of various existing relevant policies, laws, and regulatory frameworks and arrangements. Often, major or complex changes are needed to existing policies which implicate significant cross-agency regulatory issues. For many legislative drafters, nuclear is a highly specialized, complex and technical field, and this often leads to technical terminology and definitions being used in national legislation.

To address these and other challenges, the IAEA's legislative assistance programme supports national authorities. It is implemented within the IAEA's technical cooperation programme to create awareness of and build capacity in nuclear law, so safety and security standards are developed, including those for ionizing radiation facilities and their licensing, regulations, and inspections.

The IAEA's multi-faceted support includes meeting with decision makers, policymakers, senior officials and legislators such as parliamentarians; conducting national, sub-regional and regional workshops for a broad range of officials; and reviewing drafts and enacted nuclear legislation. The programme further builds capacity through training sessions, such as at the Nuclear Law Institute — the annual two-week nuclear law training programme focused on legislative drafting organized by the IAEA. Over the past decade alone, more than 500 officials have been trained at the Nuclear Law Institute and over 200 bilateral legislative drafting activities have been conducted, while 53 national workshops and 18 regional and sub-regional workshops have been held.

More recently, webinars on nuclear law have furthered nuclear law dialogue with Member States. During the past ten years, more than ten countries in Asia and the Pacific, ten in Europe and over twenty in Africa have adopted new or revised legislation with IAEA drafting assistance. Brunei Darussalam and the Philippines, with their newly installed cyclotrons, and Jordan, with its accelerators, are just some examples of countries benefiting from this assistance. Finally, the IAEA's Handbooks on Nuclear Law, particularly the Handbook on Nuclear Law: Implementing Legislation remain the go-to publications in this field.

Over the past decade alone, more than 500 officials have been trained at the Nuclear Law Institute.
(Photo: D. Calma/IAEA)

What you need to know about ion beams

By Puja Daya and Sotirios Charisopoulos

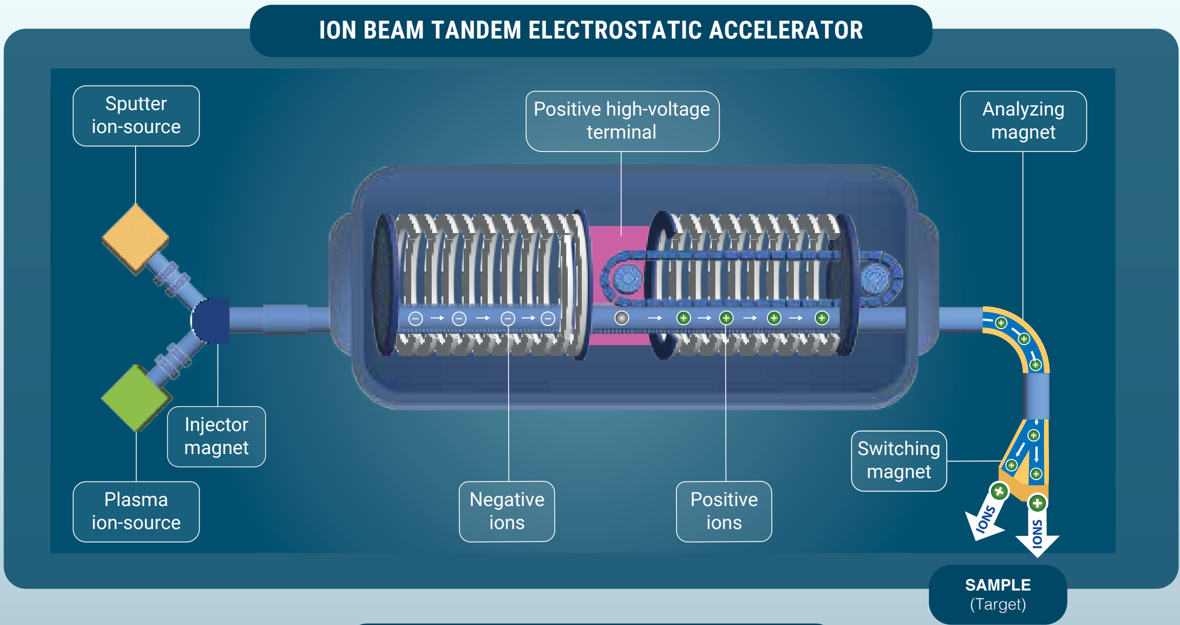
Whether it is determining the origin of pollutants, characterizing contaminants in food, imaging individual biological cells or putting a date to historical objects, scientists use ion beams to help give us answers. But what are ion beams and how are they used?

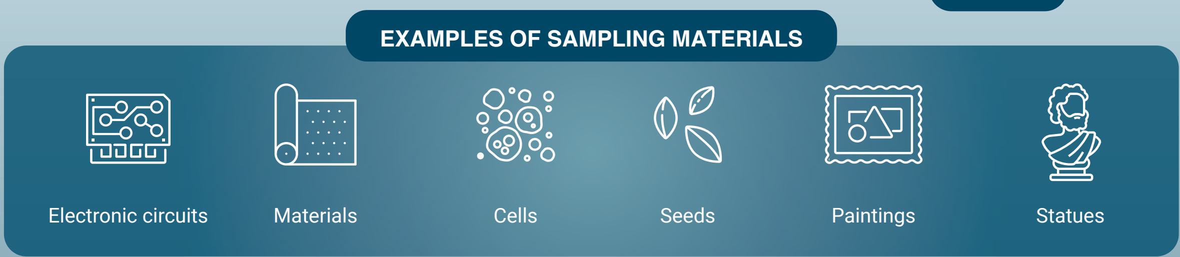
Ion beams are, as their name suggests, streams of electrically charged atoms. The ions in a beam are produced by special instruments called ion sources. They gain speed when entering an electric field, which is produced in a particle accelerator, and are steered and focused by magnetic fields to travel in parallel trajectories inside a vacuum in a metal tube. Depending on the type of accelerator, ion beams can be accelerated at a velocity close to the speed of light.

In the case of tandem electrostatic accelerators (see figure), ion beams are bombarded into a material sample or object. The interaction with the material can force the ions in the beam to change course, or the collision can cause particles or radiation to be released, mainly in the form of X-rays or gamma rays. This radiation can then be detected and analysed.

The properties of the energy and of the emitted radiation reveal details about the composition of the bombarded sample, such as whether it is crystalline or not, its hardness, and physical properties which are of interest for emerging technologies. Bombarded sample materials or objects may also vary in shape and phases of matter, and can be thin foils; small pellets of soil; human, animal or plant cells; seeds; rocks; liquids; or even historical artefacts or statues. Depending on the material's form and composition, bombardment may occur in a vacuum or in air.

Due to their unique analytical and modification capabilities, accelerated ion beams are used in many applications. In plant mutation breeding, ion beams are used to irradiate plant material or seedlings in order to to accelerate





their natural evolution process by inducing mutations, to develop higher yielding or disease and drought resistant crops.

Protons and other ions are used extensively to produce the radioisotopes needed to create radiopharmaceuticals for diagnosing and treating cancer. In cancer therapy, proton and carbon ion beams are used to bombard cancerous tumours, especially when no alternative therapy is possible. These beams deliver energy to a tumour to heat it up and disintegrate it.

With increasing demand for stronger and better materials, a wide variety of ion beams are also used to modify material properties, reinforcing their resistance. One example is for spacecrafts or fusion reactors which require materials to operate under harsh radiation environments.

Electron beams

Similar to ion beams are electron beams — a stream of electrons generated by electron sources in a variety of accelerators. They are used to produce X-rays, which in medical therapy are applied to irradiate and destroy cancer cells. Electron beams or X-rays are also employed to irradiate food and kill dangerous bacteria without degrading their nutritional value, quality or taste.

Future IAEA ion beam facility project

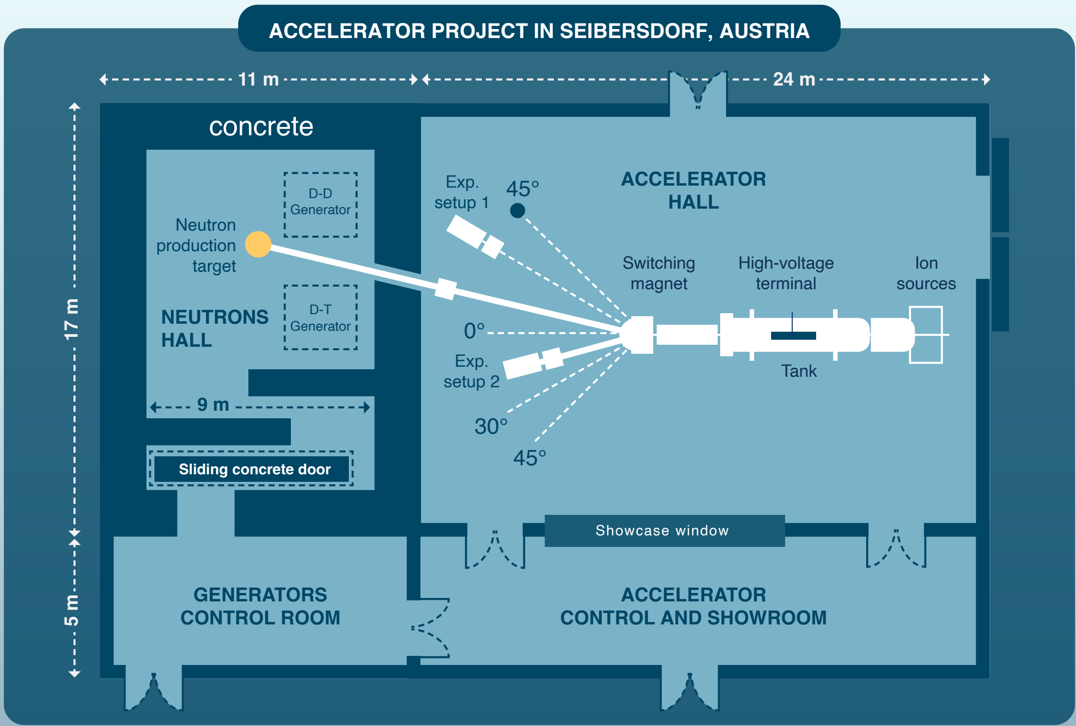
Countries around the world can benefit from the use of ion and electron beams, and the IAEA is planning to establish its own state-of-the-art tandem ion beam facility (IBF) in Seibersdorf, Austria. With this accelerator, the IAEA will support research and help educate and train scientists from around the world on the diverse applications of ion beams, including the production of secondary particles as neutrons.

"Particle beams are unique probes that can be used not only to better understand the universe, but also to analyse and take advantage of physical processes capable of improving life and support economic growth," said Danas Ridikas, Head of the Physics Section at the IAEA. "Particle accelerators are a cost-effective investment to help achieve sustainable development. With a new tandem ion beam accelerator, the IAEA can further help countries to strengthen their capabilities in accelerator technologies and their applications."

In order for the IBF project to accommodate the tandem accelerator, the required infrastructure and the associated instrumentation, as well as the resources for its operation, the IAEA is looking to raise about €4.6 million.

"Particle beams are unique probes that can be used not only to better understand the universe, but also to analyse and take advantage of physical processes capable of improving life and support economic growth."

— Danas Ridikas, Head, Physics Section, IAEA



(Graphics: A. Vargas Terrones/IAEA)

Industrial irradiation for a better world

By Michael Amdi Madsen

The word 'radiation' strikes fear in some people, but irradiation has played an invisible, beneficial, and often critical role in industry and food safety for over 100 years. Whether applied to sterilizing medical devices, sanitizing fresh produce or strengthening industrial polymers, irradiation technologies are an integral part of the modern world.

To better understand the importance of industrial irradiation, and learn how its technologies are developing, we spoke to Paul Wynne, Chairman and Director General of the International Irradiation Association (iia).

The iia is a not-for-profit organization made up of corporations, research institutes, universities and governmental bodies from around the world. It supports the global irradiation industry and scientific community.

Q: Where has accelerator-based industrial irradiation had the most impact and where do you see this technology moving?

A: Accelerators have been used on an industrial scale for about 60 years to improve the properties of polymers. One of the main applications is the treatment of cable insulators to increase their resistance to high temperatures, which contributes to fire safety and equipment durability. There are many other applications based on other chemical modifications induced by electron beams, such as the creation of wood–plastic composite for flooring or the manufacture of foams used in the automotive industry. Many of these applications are proprietary and applied on manufacturing sites.

The introduction of high power accelerators broadened the range of products that could be processed, allowing the technology to compete with gamma irradiation emitted from the radioisotope cobalt-60. The expanded range of products that could be treated included the sterilization of medical devices and packaging, pharmaceutical and cosmetic ingredients, and the microbial control of food. To date, gamma irradiation has remained predominant for these applications.

"It is likely that much of the growth of the traditional gamma irradiation market will go to accelerators in the future."

— Paul Wynne, Chairman and Director General, International Irradiation Association

Q: Is there a shift from irradiation using a radioactive source towards accelerator-based technologies?

A: There is a drive for this, and it mainly concerns the sterilization of medical devices where the demand for medical devices and hence sterilization is rapidly increasing.

Irradiation is the preferred method for a little under half of the global volume of devices requiring sterilization, with gamma sterilization accounting for more than 80 per cent of these volumes. Various circumstances, some of which might be temporary, have recently prevented the cobalt-60 supply from keeping pace with the increase in demand. Medical device manufacturers usually have no preference for one method over another, they simply want their products properly sterilized.

Gamma sterilization from cobalt-60 sources has two great virtues: simplicity and reliability. Accelerators also have advantages: the fact that only electricity is needed to power them and the possibility to pause the emission of ionizing radiation. The forces of the market will decide which of these technologies will be dominant in the future, but, for the moment, it is important that they all remain available because they are all needed to meet sterilization demand.

It should be noted that, in terms of treatment capability, anything that can be treated by electron accelerators can be treated by gamma radiation, but the converse is not true. However, some accelerators can be fitted with a metal target that will convert the electron beam into X-rays which have characteristics similar to gamma radiation.

Q: Demand for accelerator-based industrial applications is growing, particularly in developing countries. What challenges do these technologies need to overcome to become more accessible?

A: It is likely that much of the growth of the traditional gamma irradiation market will go to accelerators in the future. The number of accelerator suppliers exceeds the number of cobalt-60 suppliers, but remains limited to a dozen or so for high-energy and high-power machines, and much less for accelerators with X-ray capability. The development of X-ray systems remains limited but is growing rapidly from a low base.

Accelerators have not yet been significantly adopted in many developing countries. The high investment required, the complexity of the machines compared to gamma irradiators, and the unavailability of an abundant and stable electricity supply are among the main reasons. Human resources, financial constraints, and fulfilling safety requirements are obstacles that could probably be overcome more easily than infrastructure and market size issues. For the moment, accelerator-based technology does not appear to be well-suited for all developing countries.

Q: The iia and the IAEA work together on different initiatives, such us international conferences and workshops for young researchers. How does this benefit the increased use of accelerator technology?

A: The objectives of the association align with some of the IAEA's objectives. The iia is technology neutral in promoting the safe and beneficial uses of radiation technologies. While the counterparts of the IAEA are governments and their agencies, the iia mainly represents the industrial irradiation market. The iia collaborates with the IAEA in a growing number of initiatives.

Q: What accelerator-based industrial irradiation development are you most excited about? Would it be a 'game changer'?

A: In-line irradiation with low energy electrons and low energy X-rays is a very promising new approach. Based on the use of miniaturized accelerators or emitter lamps, this innovation could bring irradiation within the reach of manufacturers in many sectors. The penetration of low energy rays into materials limits potential applications, but the emitters have the advantage of being compact and can be integrated into manufacturing lines. Initial applications include the sterilization of syringes before filling in the pharmaceutical industry and the sterilization of materials at high speed on aseptic packaging lines for milk or soft drinks.

Just to give you an example, a Swiss company has developed a machine for decontaminating food ingredients that is about the size of a large cabinet. Such systems are also used in pest control using the sterile insect technique, of which the IAEA is a champion, and for research in radiation biology. More efforts are required to expand the field of potential applications, especially using compact low energy X-ray systems, but there is little doubt that this might be a game changer.

MYRRHA: An accelerator driven system to manage radioactive waste

By Hamid Aït Abderrahim

Hamid Aït Abderrahim is the Deputy Director General for International Affairs at SCK CEN, and Director of the MYRRHA project and its non-profit organization. A professor of reactor physics and nuclear engineering at the Catholic University of Louvain, he is a coordinator and partner of various European Commission projects related to progressive nuclear systems, separation of high activity nuclear waste and transmutation management. A member of various scientific councils, research organizations and international institutes, in 2014 he was nominated as Grand Officer of the Order of the Crown by the King of Belgium for his contributions in the fields of nuclear energy science and closing the fuel cycle.

One major — and false — objection sometimes cited against nuclear power is that "there is no solution to the nuclear waste problem". Spent nuclear fuel that has not been reprocessed remains radiotoxic above levels found in natural uranium ore for approximately 300 000 years, and the vast majority of uranium and plutonium remains unburned within it. While technical solutions for such long term disposal exist, there is another route: nuclear fuel recycling.

Both the uranium and plutonium from spent fuel can be recycled by reprocessing and used in new nuclear fuels for further power generation. However, the residue from standard reprocessing leaves minor actinides — elements close to uranium in the periodic table which cannot be burned in current power reactors. Radioactive waste containing them still requires 10 000 years to return to natural levels.

MYRRHA (Multi-purpose Hybrid Research Reactor for High-tech Applications) is a project currently under construction at the Belgian Nuclear Research Centre (SCK CEN) based on the accelerator-driven system (ADS) concept that aims to address actinides, and, more particularly, the minor ones. The project seeks to demonstrate, at the engineering level, ADS and the feasibility of the transmutation of the minor actinides on an industrial scale. By reducing radiotoxicity, this could reduce the volume of high level radioactive waste by 99 per cent and the time required for storage to just 300 years.

MYRRHA's design differs from most current reactors in two important aspects. First, it uses fast neutrons, which are required to fission the minor actinides. Second, it can operate in a subcritical mode — i.e. without causing a self-sustaining chain fission reaction — as it is coupled to a high energy proton accelerator producing the needed primary neutrons in the centre of the reactor core via spallation reactions. This is necessary to ensure reactivity control when burning the minor actinides and provides the additional advantage that, as soon as the accelerator stops, the chain fission reaction stops and the reactor shuts down. As an essential safety measure, it is designed so that the residual decay heat can be removed by natural circulation without any active system or intervention.

In order to transmute a substantial proportion of the world's spent fuel waste, a network of industrial facilities will be required. To date, the technologies involved in MYRRHA have been proven individually on the laboratory scale at experimental facilities. Therefore, MYRRHA is a pre-industrial pilot plant aimed at integrating and testing the technologies at scale while substantially increasing reliability.

There are many scientific, engineering and regulatory challenges that will need to be met during the development of this first-of-a-kind project. A pre-licensing review undertaken by the Belgian nuclear regulatory agency, after close consultation with the project

developers, has not revealed any concerns strong enough to put the future licence of MYRRHA in doubt. We hope this will attract many young people in Belgium and from elsewhere to the nuclear field, which the country feels is of great importance.

While the main emphasis of the project is on managing radioactive waste, there are many other applications of this facility in cutting edge research and development. The MYRRHA project is divided into three stages. The first is already under construction and will see the lower energy (100 megaelectronvolt (MeV)) part of the proton accelerator complex completed, with many of the research activities expected to begin in around 2027. These will be centred around the Isotope Separation On-Line (ISOL@MYRRHA) system, which can select individual isotopes for use in radiopharmaceuticals and produce radioactive ion beams for a wide variety of nuclear physics experiments supplemented with a Full Power Facility (FPF) suited for fusion materials research.

The high precision of measurements that can be made on radioactive beams delivered by ISOL@MYRRHA may also contribute to understanding the validity of the ‘standard model’ of particle physics. If the first stage is successful and demonstrates the unprecedented accelerator reliability needed for ADS, the second stage will see the proton accelerator brought to full power (600 MeV). The final stage will be the construction of the sub-critical reactor itself. Lead–bismuth (Pb–Bi) is used as a coolant to remove heat generated from the nuclear reactor. The design of reactor core is flexible and can be loaded with mixed-oxide fuel, minor actinides and targets for medical isotope production. It will offer rigs for irradiation and corrosion testing of future structural materials for fast fission and even future fusion reactors. The MYRRHA Pb–Bi cooled reactor can be used as an experimental technology test plant for fourth generation lead cooled fast reactors.

The Belgian Government has invested about €200 million in the MYRRHA project so far, and supplemented €558 million in 2018 for the period 2019–2038 based on an overall project estimate of about €1.6 billion. A not-for-profit entity has been created. This will enable MYRRHA to attract future investment from foreign governments and entities to move on to its second and third phases, and to operate as an international organization. MYRRHA has been listed in the European Strategy Forum on Research Infrastructures (ESFRI), which is composed of projects identified by research communities as leading edge, and the Nuclear Physics European Collaboration Committee (NuPECC) included ISOL@MYRRHA in its long-range plan of major European nuclear physics facilities. The European Strategic Energy Technology Plan (SET Plan), designed to encourage low carbon technologies, also lists MYRRHA, which enables it to receive financing from the European Investment Bank.

The potential for recycling uranium and plutonium into fuel for fast spectrum systems also reduces the demand for mining of uranium ore and substantially increases the amount of energy recovered from it. Increased efficiency of raw material use and waste reduction are in high demand by many industries, and for these reasons MYRRHA has been integrated into the Belgian national policies for strategic investment and the integrated national energy and climate plan.

A 3-D render of the full MYRRHA facilty.
(Photo: MYRRHA)

Towards a 'just' energy transition
Nuclear power boasts best paid jobs in clean energy sector

According to new research, investments in nuclear energy production generate more and higher paying jobs than investments in other low carbon sources of electricity.
(Photo: IAEA)

According to new research presented at an IAEA event, the move to clean energy will generate more jobs than are lost with the transition away from fossil fuels, and the highest paid jobs will continue to be in nuclear power, which provides significant and sustainable employment benefiting local and regional economies.

With more than 130 countries either committing to or considering a target of net zero greenhouse gas emissions by 2050, preparing for how this energy transition will affect the job market is critical. Representatives from the clean energy industry joined a recent IAEA webinar on how to ensure rising living standards and job creation as energy investments align to meet climate goals.

"Moving away from the use of fossil fuels must not leave anyone behind — this is the concept of a 'just' transition," Henri Paillere, Head of the IAEA Planning and Economic Studies Section, said at the webinar "Investing in Low Carbon Technologies: Job Creation for Just Energy Transitions". "Investing in all clean technologies is needed on a massive scale and this must be done in a way that creates jobs and economic growth, and that supports sustainable development."

Investments in clean energy sources, such as solar, wind and nuclear, have a positive impact on gross domestic product (GDP) that is two to seven times stronger than spending on fossil sources, such as gas, coal and oil, according to an International Monetary Fund (IMF) working paper. An analysis presented by the International Renewable Energy Agency (IRENA) at the webinar predicts that, in a scenario where the global temperature rise is limited to 1.5° Celsius, consistent with global climate goals, jobs in the renewables sector could grow from 12 million to 38 million by 2030.

Other energy transition-related jobs could grow from 16 million to 74 million over the same period, said Michael Renner, Programme Officer in the Knowledge, Policy and Finance Centre at IRENA. By contrast, conventional energy jobs would decline from 39 million to 27 million.

According to the IMF paper, investments in nuclear power produce the biggest economic multiplier effect of any clean energy source. The paper also showed that nuclear power creates about 25 per cent more employment per unit of electricity than wind power, while workers in the nuclear industry earn one third more than those in the renewables sector.

Similar findings were presented by Philippe Costes, Senior Advisor at the World Nuclear Association (WNA). "Nuclear offers jobs with higher wages than any other energy technology, roughly 25–30 per cent higher. But, importantly, while nuclear provides jobs locally around the plant and in regional economies during construction, similar to wind, only nuclear provides significant and sustainable jobs to the local and regional economies during operation," Costes said at the webinar.

WNA research has found that nuclear power provides about 25 per cent more employment per unit of electricity in France and in the United States of America than wind power, and these jobs are well paid, long term and predominately local, Costes said. The long term economic benefits of nuclear are also reflected in the rising level of localization for newcomer countries, he added, pointing to the example of the Republic of Korea, whose scaling up of nuclear power coincided with its economy becoming the 11th largest in the world by the mid-1990s. Nuclear produces almost one third of the Republic of Korea's electricity.

According to the International Energy Agency (IEA), around 60 per cent of the 30 million new workers needed for clean energy, energy efficiency and low-emissions technologies by 2030 will be in new and highly skilled jobs, requiring post-secondary education such as vocational certificates or university degrees. Governments and academic institutions need to start putting in place policies to develop this workforce of the future, said Daniel Wetzel, Head of the Tracking Sustainable Transitions Unit at the IEA.

— By Nicholas Watson and Lucy Ashton

Strain of foot-and-mouth disease in Tunisia identified in record time with IAEA and FAO support

A veterinarian collects an oral sample from a cow suspected of having foot-and-mouth disease in Nabeul in north-eastern Tunisia.

(Photo: T. Ben Hassine/Ministry of Agriculture, Water Resources and Fisheries of Tunisia)

In early 2022, a virology laboratory in Tunisia received oral samples from cows that were suspected by veterinarians of having foot-and-mouth disease (FMD). FMD is a highly contagious disease that affects cloven-hoofed animals, such as cows, pigs and goats, and it can lead to the disruption of regional and international trade of animals and animal products. The disease is characterized by fever and blister-like sores between the hooves, in the mouth, and on the tongue and lips.

Within days of submitting the samples to a genetic sequencing service, Soufien Sghaier, a virologist at the Virology Laboratory of the Tunisian Veterinary Research Institute(IRVT), received results that helped confirm that a strain of FMD was circulating. Sghaier was able to notify veterinary authorities to implement control measures in order to prevent the disease from spreading. This timely confirmation was made possible by the IAEA, in partnership with the Food and Agriculture Organization of the United Nations (FAO), which facilitates the sequencing service and provides the training needed to process the results.

"We received the sequencing results from a suspected case of FMD suspicion very quickly. Samples were sent to a laboratory in Berlin on Friday, and we received the sequencing results on Monday afternoon," Sghaier explained. "This allowed us to perform an analysis to identify the specific strain of FMD in record time. By Tuesday, we had sent the report on the FMD strain to the veterinary authorities.” Strains of FMD need to be identified in order to select or develop effective vaccines.

Genetic sequencing is important for determining whether a circulating disease is endemic or whether it has been imported from elsewhere. “Genetic sequencing can help us to understand which cluster a pathogen — an organism that causes disease — belongs to and which vaccine is effective against the pathogen,” said Ivancho Naletoski, Animal Health Officer at the Joint FAO/IAEA Centre of Nuclear Techniques in Food and Agriculture. A phylogenetic tree that maps the lineage of a species can be created based on genetic sequencing.

“With our phylogenetic analysis, we determined that we already had a vaccine that could protect our cattle. The veterinary authorities implemented perifocal vaccination to reduce the risk of FMD spreading,” Sghaier said. Perifocal vaccination, or buffer vaccination, can help prevent the virus from spreading to other geographical regions.

The IAEA–FAO genetic sequencing service

The cost-free genetic sequencing service enables countries to perform sequencing for the in-depth analysis of pathogens. To date, more than 5300 samples have been submitted by 30 laboratories from 24 countries across Africa, Asia and the Pacific, Europe, and Latin America.

“Installing genetic sequencing technologies in local laboratories is quite expensive,” Naletoski said. “There is not a massive need to sequence every single isolate; only a few samples from selected outbreaks are needed. In terms of economic feasibility, it is wise to enable a pipeline for counterparts to have access to a sequencing service.” The IAEA has developed and disseminated step-by-step technical instructions to process raw data and generate phylogenetic trees for locally circulating pathogens based on the results provided.

In addition, the Joint FAO/IAEA Centre hosted training courses for laboratories on how to use the service in Morocco in 2017 and in Argentina in 2018. At the national level, the service plays a role in disease monitoring programmes. At the global level, the service supports relevant studies and contributes to the global scientific community. Thus far, more than 30 articles have been published in peer-reviewed journals, based on results obtained through the sequencing service, with tens of sequences published in open-source databases.

— By Joanne Liou

Improving radiation protection in medical procedures using fluoroscopy

Less risky than traditional surgery, and with shorter hospital stays and faster recovery times, image guided, minimally invasive procedures are being used more and more frequently worldwide. In 2020, a total of 24 million such procedures were performed — a more than 6-fold increase since 2008. However, there can be a catch: without the proper precautions, patients and medical staff alike can be exposed to unnecessary radiation from the X-rays that fluoroscopy uses for doctors to ‘see’ what they are doing inside the body.

“We have identified new challenges for radiation protection due to the technical developments and increases in the complexity of these procedures, and potential gaps in guidance and training to improve radiation protection of patients and staff,” said Jenia Vassileva, Radiation Protection Specialist at the IAEA.

Fluoroscopy shows a continuous X-ray image — produced by a beam passed through the body — displayed on a monitor.

At a recent IAEA meeting, as part of support to the medical community, over 100 experts from 42 countries and 18 international organizations and professional bodies discussed progress made and challenges for radiation protection in fluoroscopy guided interventional procedures. They focused on ways to enhance the radiation protection of patients and medical staff when applying these procedures, which can cause skin injuries in patients and radiation-induced cataracts in medical staff performing interventional procedures.

Management of radiation protection of patients and medical staff

Often, tissue reactions involve only skin reddening or the loss of hair, but, in a few cases, more severe reactions, such as ulceration or dermal necrosis, can arise — sometimes weeks, months or even years later.

“Factors associated with high doses are the patient size and the medical complexity of the procedure, which require prolonged fluoroscopy; however, in most cases, unintended severe tissue reactions occur as a result of the lack of knowledge and awareness of the operator,” said the Chair of the meeting, Stephen Balter, a professor of clinical radiology and medicine at Columbia University, United States of America.

Fluoroscopy shows a continuous X-ray image — produced by a beam passed through the body — displayed on a monitor. The radiation protection of patients and medical staff during this procedure is paramount.

(Photo: Desislava Kostova-Lefterova, National Cardiology Hospital, Sofia, Bulgaria)

Hal Workman, a patient who suffered from a serious skin injury resulting from a cardiac intervention 14 years ago, said: “It took more than a year before anyone could identify that my prolonged fluoroscopy procedure had caused my injury, and for over 15 months I had no more than two hours of sleep at any one time. This was the worst pain you can imagine.”

Participants also learned about the latest developments in fluoroscopy technology, including a type of skin dose map with a colour or greyscale visual distribution of radiation doses. This provides operators with information on dose monitoring in order to better adjust the procedure’s settings and avoid injuring the patient’s skin.

“Twenty years of effort has resulted in a dramatic reduction of cases of skin injuries,” said Balter. “Improvements in fluoroscopic equipment and in the medical devices used for these procedures are major contributors.” He emphasized that it is important to plan, especially for patients with obesity and those undergoing multiple procedures, and to constantly monitor the dose delivered and proactively follow up on possible skin reactions when a substantial amount of radiation needs to be used in a complex procedure.

In addition, monitoring doses to medical staff is still a challenge in many countries. Efforts to increase radiation protection involve, for example, the use of real time electronic dosimeters, video systems for the automatic tracking of staff, and virtual simulators.

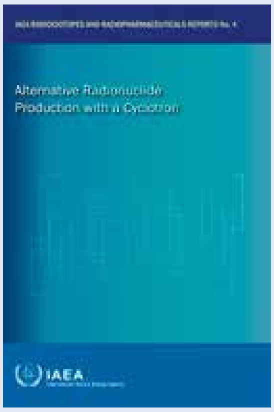
Raising awareness among medical staff about radiation protection would also go a long way towards decreasing the exposure of staff and patients, Vassileva said. Participants at the meeting said that practice-oriented training using videos, such as the new IAEA practical tutorials on radiation protection in interventional procedures, are effective in this regard.

IAEA study to increase awareness

To bridge the existing gaps in data on tissue reactions in patients, and to compare practices internationally, the IAEA has launched an international study of patient doses and tissue reactions from fluoroscopy guided interventional procedures.

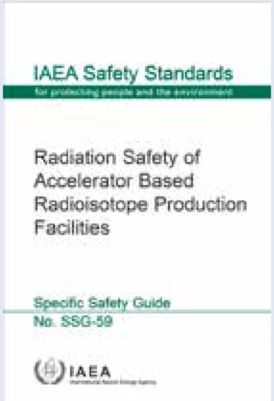
“Our goal is to collect data globally, which will help us to update the dose values used to initiate follow-up procedures for patients at risk of skin reactions.” said Vassileva.

— By Margherita Gallucci and Natalia Ivanova



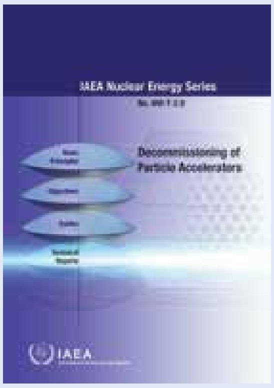
Alternative Radionuclide Production with a Cyclotron

Cyclotrons are currently used for the preparation of a wide variety of radionuclides that have applications in single photon emission computed tomography (SPECT) and positron emission tomography (PET). Consequently, there is high demand from IAEA Member States for support in the area of radiopharmaceutical production using cyclotron produced radioisotopes. This publication describes the potential radionuclide production routes using cyclotrons in different energy ranges and provides methods for the development of targets and provides details of the chemistry for the separation of radionuclides from target materials. The readership of this publication includes scientists, operators interested in putting this technology into practice, technologists already working with cyclotrons who wish to enhance the utility of existing machines, and managers in the process of setting up radionuclide facilities in their countries. Students working towards higher level degrees in related fields may also benefit from this publication.



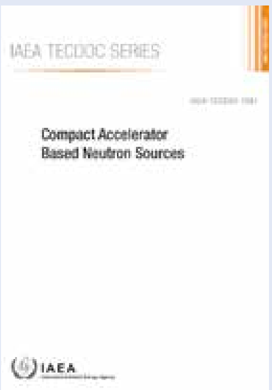
Radiation Safety of Accelerator Based Radioisotope Production Facilities

Radioisotopes are used worldwide in a range of medical, industrial, research and academic applications. A large proportion of these radioisotopes are produced in particle accelerators, and the number of institutions that operate linear accelerators or cyclotrons and manufacture and distribute radiopharmaceuticals, for example, is significant and increasing. The production of radioisotopes using particle accelerators poses significant radiation hazards to workers, members of the public, and the environment when accelerators are operated without adequate radiation safety measures. This Safety Guide provides practical guidance for implementing radiation protection and safety measures in such facilities involved in the production and use of radioisotopes.



Decommissioning of Particle Accelerators

This publication presents information on experience and lessons learned from implementation of decommissioning projects for particle accelerators. Based on this information, and highlighting typical issues and concerns, the publication provides practical information for all those having a role in this process. The publication is written for operators of accelerator facilities, particularly those approaching the decommissioning stage, or maintaining a facility in a deferred dismantling state, as well as for regulators, waste managers, decision makers at government level, local authorities, decommissioning contractors and designers of accelerators. It is anticipated that the lessons learned described in this publication will contribute to decommissioning planning during the design stage of new facilities, hence minimizing the generation of radioactive waste without compromising structural characteristics and the effectiveness of the construction.



Compact Accelerator Based Neutron Sources

The production of neutrons by accelerators began in the 1970s with construction of powerful proton accelerators to access neutrons via spallation. At the same time, low energy driven neutron processes emerged for neutron production using electron accelerators, ion beam accelerators, cyclotrons, and low energy linear accelerators. This wide variety of accelerator based neutron sources have come to be referred to as 'compact accelerator based neutron sources' (CANS). This publication provides an overview of the various types of CANS technologies that are currently available or planned in the near future. It illustrates many of the analytical and other applications of neutrons. Given the wide variety of power and costs, the publication also aims to show that in addition to replacing national medium flux research reactors for certain functions, smaller regional neutron sources may become viable, which may eventually broaden access to neutron facilities.

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