
The future

research is Rutherford Back Scattering Spectrometry (RBS). Helium ions are the preferred projectiles, since at elevated energies (above 3 MeV) nuclear resonance scattering can be used to detect photons associated with target molecules containing elements such as carbon, nitrogen or oxygen.

Due to the large amount of available data on nuclear reactions in this energy range, activation analysis (detecting trace elements by irradiating the sample) can be performed with charged particles from accelerators over a wider range of atoms than with the conventional use of neutrons, which is more suited to light elements. Resonance reactions have been used to detect trace metals such as aluminium, titanium and vanadium.

Hydrogen atoms are vital to the material performance of several classes of materials, such as semiconductors, insulators and ceramics. Prudent selection of the projectile ion aids the analysis of hydrogen composition; the technique is then a simple measurement of the emitted gamma radiation. Solar cell material and glass can be analysed in this way.

On a world-wide basis, numerous laboratories perform ion beam analysis for research purposes; considerable work is carried out in cooperation between scientific laboratories and industry, but only a few laboratories provide a completely commercial service.

From K. Bethge, Frankfurt am Main, Germany

Particle accelerator development must rank as one of the major scientific achievements of the twentieth century. Progress in computing methods, engineering design techniques and advances in material science have all contributed to today's highly-developed, precision technology where small versatile machines are used for a wide range of applications.

The accelerator community has opportunities to expand the range of applications in industry and medicine, particularly by increasing beam intensities. In some cases, the required 'technology-step' improvements can be achieved by employing existing materials and present day techniques.

Medicine

In the competitive commercial world of radiopharmaceuticals, the trend is to employ higher intensity accelerators for lower-cost production of isotopes and to operate these machines under increasingly more stringent radiological controls.

Several accelerator manufacturers are developing higher current machines in the range 500 to 1000 microamps, demanding production targets better suited to handling heat production. One company, IBA in Belgium, has already supplied 2 mA, 18 MeV positive-ion cyclotrons with internal targetry for the commercial production of a new therapeutic isotope, palladium-103, for cancer brachytherapy. In Canada, EBCO Industries together with TRIUMF have announced the development of 1000 microamp extraction from their existing 30 MeV cyclotron.

The isotope production industry is a major opportunity for accelerator technology. Historically, material-

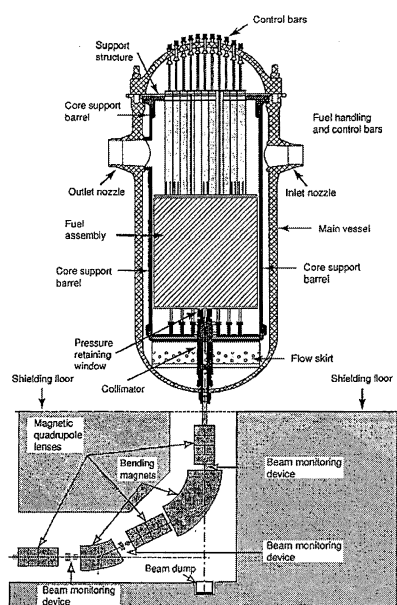
testing reactors have always provided low-cost isotopes to the industry and to medical companies; however many of these reactors are reaching the end of their lives and are not being replaced.

Diminishing research in nuclear power generation and fuel testing, combined with the dilemma on waste disposal, has made fission-based reactors less attractive. High intensity accelerators with appropriate targetry could be constructed to produce the necessary neutron fluxes in the range $10^{14-15} \text{ cm}^{-2}\text{s}^{-1}$ (e.g. spallation sources at 500 to 1000 MeV with intensities of a few mA). With no criticality issues and no fuel management problems, this type of accelerator could replace nuclear reactors for this purpose; so far no laboratory has produced such plans.

Of the present day reactor-generated isotopes, molybdenum-99 remains the most common medical isotope and is produced by fission of enriched uranium-235 in thermal neutron reactors. A proton-driven intense subcritical neutron source has been proposed recently by Yves Jongen of IBA where a 150 MeV, 1.5 mA proton beam from a cyclotron would strike a molten lead target, surrounded by a water and graphite reflector, to produce neutrons by spallation. These primary spallation neutrons would strike secondary targets containing subcritical amounts of uranium-235, producing a thermal neutron flux up to 2×10^{14} and a fission power of over 500 kW. Manufacturers could then position their own molybdenum-99 production targets in this machine and continue to produce a radiopharmaceutical grade product without the need to access a nuclear reactor. This small device would cost much less than a new research reactor.

The accelerator-based free electron

To avoid proliferation of uranium and long-term transuranic radioactive waste, new power generation ideas propose using accelerator-driven systems for fission using fuels such as naturally occurring thorium. This is a schematic of an idea suggested by Carlo Rubbia and his collaborators at CERN, using an accelerator beam to bombard a target assembly containing nuclear fuel and moderating material.



laser (FEL) at Vanderbilt University, Tennessee, has been built for research applications in medicine and biology. Early results are promising for the targeting of FEL radiation to the amide II band of proteins leading to tissue ablation without substantial damage. The free electron laser could provide a wavelength scalpel for precision surgery.

Power generation

New concepts of power generation using accelerator-driven systems for fission have been proposed using fuels such as naturally occurring thorium. Successful implementation of this technology would lead to less proliferation of uranium and less long-term transuranic radioactive waste.

At CERN, Carlo Rubbia and his collaborators have suggested employing an accelerator to produce a 1 GeV, 7 mA beam to bombard a target assembly containing nuclear

fuel and moderating material. Thorium would be used to breed fissile uranium-233 and to sustain stable energy production. Careful design of the fuel would ensure subcritical operation with a thermal neutron flux of $10^{14} \text{ cm}^{-2} \text{ s}^{-1}$, and a prototype 'energy amplifier' could generate electrical power in excess of 100 MW. Interestingly, the thermal neutron flux level of this device is close to that required for isotope production.

The original Los Alamos proposal for accelerator-driven transmutation technology (ADTT) included a programme for energy production where the fuel would be thorium and the assembly would remain subcritical.

The fuel would be embedded in a lithium-beryllium fluoride molten salt to facilitate efficient high temperature operation. The advanced study at Los Alamos has highlighted not only the demanding requirement for a high intensity accelerator but also the extreme performance levels required for the materials employed. Similar study programmes are progressing in laboratories in Japan, Russia and elsewhere.

Power generation by inertially-confined fusion is another possibility and several accelerator groups are investigating the standard deuterium-tritium reaction; the reaction of protons on boron-11 also invites attention.

Pellet design can benefit from early laser investigation but to raise the temperature above the Lawson criterion - 10 MJ energy within 15 nanoseconds - the demand on the accelerator system will be extreme. Preliminary studies on a linac-storage ring complex have already been carried out at the GSI Laboratory, Darmstadt.

The environment

Accelerator technology could benefit the environmental management of the planet in the transmutation of nuclear waste. Used nuclear fuel contains highly radioactive waste products including long-lived actinide isotopes and long-lived fission products such as iodine-129 (half-life 1.6×10^7 years). Storage of this material remains a serious public and political concern. Accelerator-driven transmutation of waste (ATW) offers a solution.

The ATW concept proposed by Los Alamos requires a 100 - 200 mA beam of protons or deuterons at up to 1.6 GeV. By interaction with a spallation target, up to 50 fast neutrons per incident particle are generated and contained inside a moderating blanket. The high neutron flux of $10^{16} \text{ cm}^{-2} \text{ s}^{-1}$ is thermalized to produce a thermal neutron flux sufficient to convert actinide products such as neptunium-237 (half-life 2.1×10^6 years) to the fissile neptunium-239 and fission product technetium-99 (half-life 2.1×10^5 years) to stable ruthenium-100.

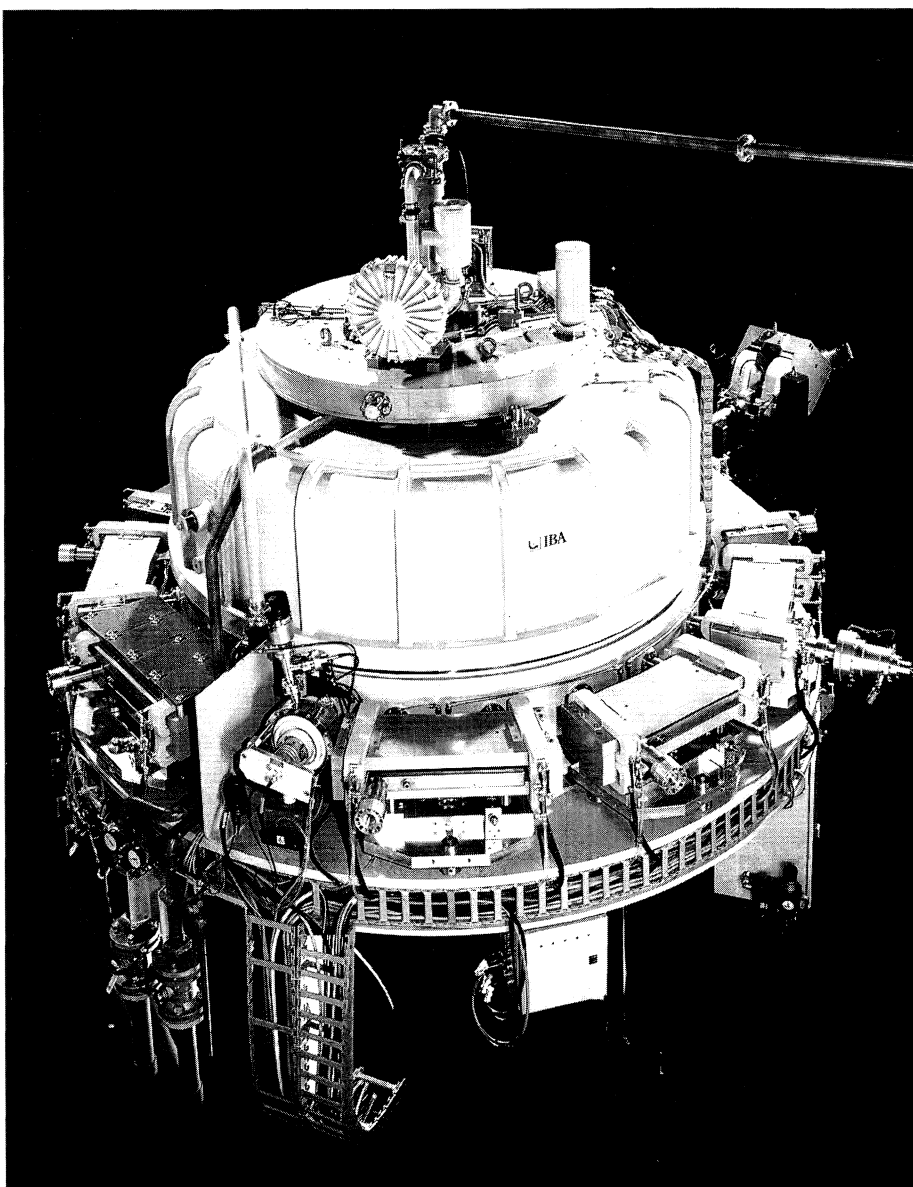
While accelerator-driven neutron sources do allow transmutation of most of the very long-lived radionuclides, the accelerator facilities and handling operations will inevitably be expensive.

Smaller accelerators can also assist in environmental control and although their application has been limited so far, the use of environmentally-invasive chemical methods is becoming less attractive and cost effective. Accelerator technology can be applied to water and waste treatment, sludge sterilization and combustion flue gas treatment in large industrial plants. The elimination of pathogens and toxins are

attractive openings for environment research using smaller accelerator devices.

This 10 MeV, 10 milliamp electron beam accelerator (the Rhodotron) is an example of a new generation of machines, purpose-designed for future industrial users, in this case for applications such as industrial irradiation and sterilization.

(Photo IBA, Louvain-la-Neuve, Belgium)



Guest editor

Guest Editor for this special issue of the CERN Courier on the applications of accelerators was Dewi M. Lewis of Amersham International plc, UK.

Dr. Lewis was educated at the Physics Department, University of Wales, Swansea, and learnt his accelerator physics as Engineer-in-Charge at the CERN Intersecting Storage Rings before joining industry in 1979 at the beginning of the boom for commercial cyclotrons. Having managed the installation of Amersham's second and third isotope production cyclotrons in the UK, his industrial experience encompassed isotope manufacturing and business management in radio-pharmaceuticals and organization of joint ventures. Following closure of several research reactors in 1990, his responsibilities extended to reactor isotope production as well as technology transfer with international laboratories. He was responsible for creation of the first Russian 'weapons to ploughshares' joint venture with the Radioisotope Association, Mayak and the Russian Atomic Energy Ministry. Dr. Lewis currently chairs the European Radiopharmaceutical Industry's committee on future reactor isotopes and is currently involved in the technical development for accelerator technology.

Amersham International is one of the world's leading isotope companies, engaged in development, manufacturing, international sales and distribution of radioisotope products in markets for healthcare, research compounds and industrial products. Formerly part of the United Kingdom Atomic Energy Agency, Amersham was one of the first companies to be privatized in 1982