PLASMA & ACCELERATOR TECHNOLOGIES FOR DEVELOPMENT

EXPANDING OPPORTUNITIES

BY THOMAS DOLAN, STJEPKO FAZINIC, C.U. ROSENGARD, & URSULA SCHNEIDER

Basic and applied research in advanced areas of nuclear science and technology has enabled many countries to realize social, economic, and environmental benefits in fields of industry, medicine, and energy. Scientific research has opened the way, for example, to more efficient industrial processes for waste removal; production of high-quality ceramics, metals, and coatings; and improved medical care and treatment.

Through a range of activities, the IAEA supports and coordinates scientific and technical research that contributes to the needs of sustainable development in its Member States. The Agency's programmes encompass applications in nuclear instrumentation, plasma physics and nuclear fusion research, and the utilization of research reactors and accelerators. This article specifically focuses on applications of plasmas and accelerator beams, highlighting activities promoting the transfer of technology and expertise.

PLASMA TECHNOLOGIES

Most people are used to thinking of the fundamental states of matter as either a solid, liquid, or gas. Yet physicists commonly work with another state of matter -- known as plasma, an ionized gas. Plasma processes — the glow in a neon light, for example, or on a giant scale, the energy of the sun -- are part of everyday life. Today, the practical and beneficial applications of plasma technologies in medicine and industry are far ranging. They include:

- surface cleaning; surface coatings; and materials testing;
- plasma-chemical synthesis manufacturing of diamond & sapphire windows;
- atomic-scale machining and modification of silicon chips;
- energy efficient sources of light;
- food preservation (anti-diffusion barriers on plastic packaging to delay oxidation);
- biocompatible materials and implants;
- medical applications (surgical and dental tools, implants, heart valves);
- hazardous waste destruction.

These and other industrial applications have a market potential of tens of billions of dollars. Many plasma technologies used for fusion research are also finding use in other fields. Plasma heating by high-power microwaves, for example, is now widely used in industry. Plasma diagnostic techniques are used for industrial applications, and small plasma machines are being used as sources of neutrons and X-rays.

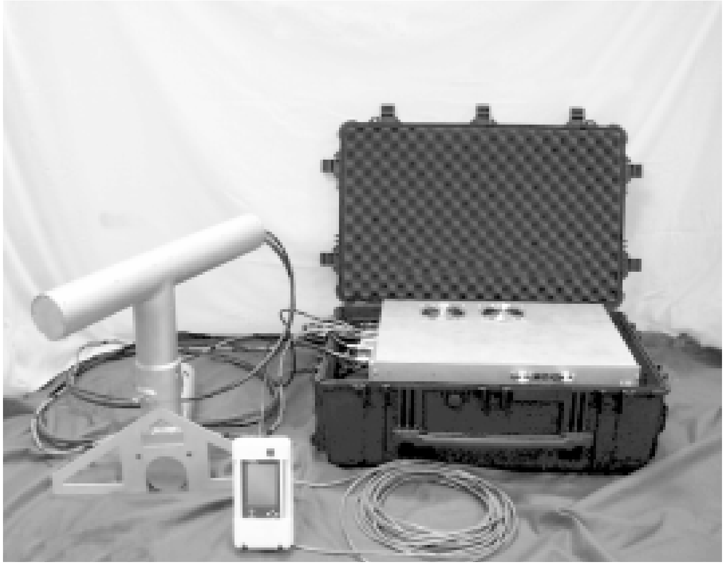
Technical Cooperation Projects. In China, the IAEA supported a technical cooperation project that is helping the country develop a plasma reactor to process toxic liquid wastes from a paper pulp mill. Now a pilot plant is being constructed to test the concept on a larger scale. If successful, this technology could be transferred to thousands of pulp mills in China and elsewhere.

Another project, in Argentina, is developing an intense pulsed neutron source that could be used for various field applications, such as mineral prospecting and explosives detection.

Coordinated Research Projects. The IAEA also has organized a coordinated research project on engineering, industrial, and environmental applications of plasma physics and fusion technologies. Notable achievements have been recorded in many of the participating countries. They include:

- *Argentina.* Surface modification of steels, titanium and other alloys was studied.

Mr. Dolan is Head of the Physics Section, Division of Physical and Chemical Sciences, IAEA Department of Nuclear Sciences and Applications, and Mr. Fazinic, Mr. Rosengard, and Ms. Schneider are staff members of the Section.



Other studies, using diffraction of synchrotron X-rays, focused on improving surface hardness of steel.

■ *Brazil.* The microstructure of hard carbon-based coatings, such as boron carbide, was studied to improve the mechanical properties, including wear resistance.

■ *China.* A study of dust-contaminated plasmas will aid quality control in material processing. Additionally, a plasma device is being studied as a possible X-ray and ion beam source.

■ *Egypt.* A device (known as a silent dielectric-barrier discharge device) has been tested as an ozone gas generator to treat sewage water, to desulfurize coal, and to remove water vapor from the natural gas in crude oil.

■ *Germany.* Amorphous hydrogenated carbon films deposited onto polymers reduced the permeability by 80% to 95%. This is comparable to reductions obtained using other permeation barrier coatings, such as aluminum and silicon oxides.

■ *Greece.* A glow discharge source of metal atom clusters was developed for construction of nano-structured materials, such as semi-conducting gas sensors.

■ *India.* A prototype plasma torch system for plasma pyrolysis of medical waste is undergoing field trials. The product gases have been measured and methods developed to prevent environmental pollution.

■ *Japan.* Special instruments were developed to measure the energy distribution functions of surface wave plasmas and of inductively coupled plasmas. The resulting concentrations of hydrocarbon and fluorinated molecules were studied to learn how to optimize parameters for semiconductor processing.

■ *Romania.* A plasma reactor was developed for materials processing.

■ *Russian Federation.* The feasibility of injecting pellets into fusion plasmas to measure the plasma parameters was demonstrated.

Such applications of plasma physics hold important benefits for the protection of materials through surface engineering; development of clean manufacturing technologies; production of new materials for future technologies; and environmental remediation.

ACCELERATOR APPLICATIONS

Thousands of accelerators are in use worldwide for a variety of applications. *(See box, page 44.)* The Agency is developing a database of low-energy accelerators and their applications. They include:

Neutron generators. High-current deuteron beams with energies of 0.1-3 MeV are injected into tritiated titanium targets, where nuclear fusion reactions produce neutrons.

Photos: Top left, the plasma reactor for disposal and recycling of paper pulp wastes in Chengdu, China. Top right, the system developed by Western Kentucky University in the USA for identifying buried objects. It is being tested for detection of buried landmines.

Such “neutron generators” are used to analyze materials by neutron absorption and scattering. Applications include physics experiments; detection of explosives and drugs; humanitarian demining; bulk analysis of coal, cements, glass, metals and agricultural products; oil well logging; mineral prospecting; non-destructive examination by neutron radiography; and medical therapy.

Agency activities include a coordinated research project on bulk hydrogen analysis using neutrons. A technical document also has been issued on neutron generator operation and maintenance. Another coordinated research project -- on the application of nuclear techniques to anti-personnel landmine identification -- is developing nuclear instruments to locate and identify buried objects. One system will be field tested for detecting landmines.

Ion Implantation. Ion beam processing can be used both to synthesize and modify materials, including metals, semiconductors, ceramics and dielectrics, with great precision. Ion implanters are used in the manufacture of advanced semiconductor chips for computers and communications systems.

About 7000 ion implantation accelerators are used by the semiconductor industry. Ion implantation requires special accelerators, able to implant ions of most elements of the periodic table, and to scan the beam uniformly over a sample.

This technology is also used to deposit thin film coatings for improvement of wear resistance, friction and corrosion for specialized tools used in industry and in medicine. For example, alloys of titanium, aluminum, and vanadium have excellent biocompatibility, good strength and corrosion resistance, but lack hardness and wear resistance. Nitrogen implantation improves the wear performance of these alloys by a factor of 1000, allowing their use as hip-joints for a much longer time.

Ion Beam Analysis. The most common ion beam analysis (IBA) methods are PIXE (Particle Induced X-ray Emission), RBS (Rutherford Backscattering Spectrometry), ERDA (Elastic Recoil Detection Analysis) and NRA (Nuclear Reaction Analysis). All elements can be detected with the IBA techniques. NRA and ERDA are more suitable for light elements and in particular for hydrogen; RBS and PIXE can detect heavier elements.

Typically, small electrostatic accelerators of about 2 to 3 MV terminal voltage are used. There are about two hundred facilities worldwide, including those used in about 20 developing countries. Using a finely focused beam of ions, most of the IBA methods may be used for imaging of elemental concentrations. Low-current methods can be used as a controllable radiation source probe to image the morphology, crystal structure, and density of materials, or to study the properties of electronic devices.

The most widespread applications are for materials development, environmental pollution studies, biomedical research, geology, and archeometry. Because of the information that they provide, RBS, ERDA and NRA are a valuable complement to more conventional surface analytical techniques, and they have unique features which make them indispensable for certain problems. They enable analysis of a wide variety of samples in

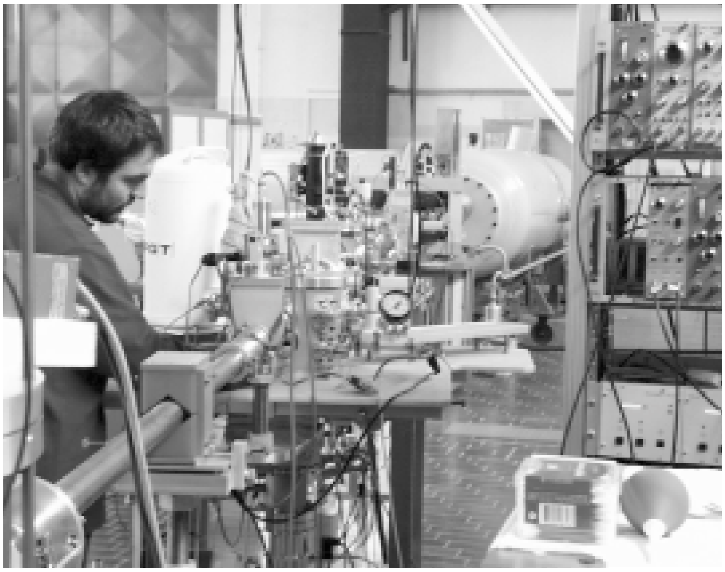


Photo: The ion beam analysis accelerator at the Josef Stefan Institute in Slovenia.

APPLICATIONS OF ACCELERATORS

ELECTRON ACCELERATORS

■ Low-Medium Energy Electron Accelerators. *Application:* Hospitals, radiation processing, radiation treatment. Applied for cancer therapy; materials enhancement, medical equipment sterilization; food preservation; pollution abatement. About 7000 worldwide (6000 hospitals, 1000 for materials enhancement, sterilization, and pollution prevention).

■ Synchrotron Radiation Sources. *Application:* Research. Applied for materials research; life sciences. Fewer than 50 worldwide.

ION ACCELERATORS

■ Neutron Generators. *Application:* Neutron activation analysis. Applied for well logging; industrial process control & analysis; detection of explosives & drugs.

■ Ion Implanters. *Application:* Ion beam treatment of materials. Applied in production of computer chips; wear & corrosion resistance; human joint implants. About 7000 such accelerators worldwide.

■ Low-Medium Energy Ion Accelerators. *Application:* Ion beam analysis & accelerator mass spectrometry. Applied for detection of trace elements; production of radioisotopes for medical diagnosis & therapy; cancer therapy by ion beams. Several hundred such accelerators worldwide.

■ Spallation Neutron Sources. *Application:* Research. Applied for high-tech materials development; nuclear waste transmutation. Approximately ten such accelerators worldwide.

fields such as materials science, art, archaeology, and biology.

The IAEA is supporting a range of projects in Member States.

■ *Slovenia.* Under a technical cooperation project at the Josef Stefan Institute in Ljubljana, a modern IBA research and education facility has been established. The institute plans to equip the accelerator with five beam lines for applications of IBA techniques, to implement a quality assurance programme for these techniques, and then to provide analytical services to support research and industry.

Two beamlines are in operation, and a nuclear microprobe beamline is under construction to support analysis of various samples using proton beams of micrometer and sub-micrometer dimensions. These systems will facilitate spatial distribution measurements of trace elements, such as for electronic materials and microelectronics devices. Another beamline is being prepared for RBS and ERDA measurements, to enable studies of thin layers, hard coatings and other materials.

■ *Israel.* The Agency has assisted Israel to upgrade its existing accelerator facilities for various applications. The capabilities of the 3-MeV Van de Graaff accelerator at the Weizmann Institute have been extended by dedicating two of its three beamlines to ion beam analytical techniques, for application in the control of air, water and hazardous materials. One beamline is being made operational for PIXE, PIGE (particle induced gamma-ray emission) and RBS applications.

■ *Iran.* The Agency assisted Iran to upgrade the analytical capabilities of the Van de Graaff Laboratory at the Nuclear Research Centre of the Atomic Energy Organization in Teheran. Capabilities were improved by the introduction of a nuclear microprobe.

The Agency has also supported technical cooperation projects related to IBA utilization in many other countries, including Brazil, Croatia, Chile, Greece, Lebanon, Mexico, Portugal, Romania, and Thailand.

The IAEA's Laboratories in Seibersdorf, Austria, use a dedicated beamline at the Van de Graaff Accelerator of the Rudjer Boskovic Institute (Zagreb, Croatia) for analysis of environmental samples, and a project helped to develop a microprobe beamline there. Additionally, the IAEA is supporting a coordinated research project on analysis of semiconductor materials using IBA, and it is publishing a technical document on PIXE and RBS techniques.

Accelerator Mass Spectrometry (AMS). This is the most sensitive trace analysis technique, with sensitivities of parts per trillion in some cases.

The accelerators required for AMS are similar to those for IBA, but more sophistication is required at the ion source and at the high energy end.

There are about 50 laboratories worldwide with their own AMS systems. AMS has two appealing features -- very small sample volumes can be analyzed, and stable nuclides can be used instead of radioactive nuclides.

AMS is one of the fastest methods for carbon assaying (30 minutes vs. several weeks for conventional dating techniques) and only milligram samples are required (compared with several grams for conventional techniques). AMS is also used with the cosmogenic nuclides beryllium-10, aluminum-26, and iodine-129, and it will find increasing use in studies of oceanography, paleo-climatology and geo-hydrology (groundwater resources).

Carbon-14 can be used as a tracer in a biological system with a sensitivity increased by a factor of one million beyond that possible with conventional methods of scintillation counting. Iron impurities at parts per billion in silicon chip manufacturing can produce problems, so AMS is used to diagnose the content of impurities.

■ *Israel.* The IAEA assisted the Racah Institute of Physics at the Hebrew University in Jerusalem in establishing procedures for the determination of strontium-90 in environmental samples by AMS using the accelerator at the Weizmann Institute of Science. The Agency provided expertise, training and some equipment to upgrade the existing facilities.

A feasibility study showed that the AMS method improved the detection limit for strontium-90 by a factor of two as compared with beta counting. An improved procedure for sample preparation will increase the sensitivity of the AMS method even further. As a result of the project, the local detection capability for trace elements in environmental samples has been improved.

Radioisotope Production. Accelerator methods of radioisotope production are valuable alternatives to production of radioisotopes by fission reactors. The accelerators used for the production of these isotopes are typically cyclotrons producing proton beams of 15 to 60 MeV. Accelerator produced short-lived radioisotopes are widely used in nuclear medicine because of the reduced dose to the patient. These include positron emission tomography (PET) isotopes, such as fluorine-18 and sodium-22 (useful for medical diagnosis and research), gallium-67 in citrate, rubidium-81/krypton-81m generators (for lung imaging), and various iodine isotopes, especially iodine-123. The radiopharmaceuticals using these short-lived isotopes provide maximum diagnostic information while producing minimal radioactive waste. The Agency supports several research activities and technical cooperation projects in this area.

■ *Israel.* A cyclotron facility for the production of radioisotopes has been established in Israel at the Hadassah Medical Organization and radiochemistry laboratories. The Agency assists in establishing facilities for the production of fluorine-18 labelled radiopharmaceuticals to diagnose cardiological, oncological, neurological and psychiatric diseases.

■ *Argentina.* The Agency is helping Argentina to develop cyclotron production of high purity iodine-123 radio-pharmaceuticals for the country's nuclear medicine services.

■ *Iran.* In Iran, technical cooperation projects deal with the cyclotron production of the short-lived radioisotopes titanium-201, gallium-67, krypton-81, and indium-111. The next line of products, based on fluorine-18 and iodine-123, will be used with PET facilities.

Cancer Therapy. About 6000 electron linacs have been installed worldwide for cancer therapy and some proton accelerators are also used for therapy. *(See related article, page 33.).* As part of its activities, the Agency recently conducted an Advisory Group Meeting on proton therapy.

Spallation Neutron Sources. When proton beams from powerful accelerators hit heavy metal targets, such as lead, many neutrons are ejected (by "spallation"). The quality of neutron scattering experiments is limited by the available neutron flux.

High neutron fluxes are needed in a number of applications, such as:

Neutron scattering for materials analysis. Since neutrons can penetrate deeply into matter, neutron scattering is widely used to determine the internal structure of ceramics, metal alloys, magnetic materials, superconductors, and biological specimens.

10 MeV, and typical beam powers are 1 to 100 kW. The electrons ionize atoms, breaking the chemical bonds and causing chemical reactions, dislocation of atoms, or sterilization.

Materials irradiation testing. High neutron fluxes are required to test the lifetime of materials for use in fission reactor cores and in fusion reactor walls.

Radioactive waste transmutation. Spallation neutron sources may be used to burn up excess actinide elements from spent fuel of fission reactors or to dispose of weapons-grade plutonium.

Medical therapy. A high neutron source strength would reduce the required patient irradiation time for boron neutron capture therapy. Since powerful spallation neutron sources are expensive, their neutron beams are often shared by many users from several countries, and international cooperation is important.

Electron Accelerators & Synchrotron Radiation. Electron beam processing is a versatile and economical method of enhancing the physical, chemical or biological characteristics of many materials. Typical beam energies are 0.3 to 10 MeV, and typical beam powers are 1 to 100 kW. The electrons ionize atoms, breaking the chemical bonds and causing chemical reactions, dislocation of atoms, or sterilization.

The range of applications includes, for example, crosslinking of wire and cable insulation; crosslinking of plastic film, foam and tubing; disinfection of sewage sludge and waste-water; modification of bulk polymers; rubber vulcanization; cellulose depolymerization; food preservation; curing of coatings; textile modifications; graft polymerization on film, fiber and paper; semiconductor modifications; and sterilization of medical supplies.

Specially designed electron beam systems have been used for removing pollutants from the exhaust gases. Most power plants burn fossil fuels that emit flue gases containing oxides of nitrogen and sulfur, which cause emphysema and acid rain. Poland is testing electron beams to remove these pollutants from the flue gases. A project in Iran will establish a national electron accelerator facility to introduce electron beam processing applications and promote the technology for industrial production of polymer materials.

Electron accelerators are used for material analysis as well. Electron beams from machines like microtrons or linacs with energies above 25 MeV may be used to produce high energy gamma rays for photon activation of various samples, which can then be analyzed for elemental concentrations.

High-energy electron synchrotron accelerators (several GeV) serve as bright sources of synchrotron light, which is used to analyze the structure of many materials, both organic and inorganic. The Agency is collaborating with the International Centre for Theoretical Physics in Trieste, Italy, to provide training in synchrotron radiation applications to scientists from developing countries.

SUSTAINING PROGRESS

Through a variety of mechanisms, the IAEA is assisting its Member States to apply plasma and accelerator technologies in various fields. These applications yield practical benefits in industry, research, environmental monitoring, education, and health care, thus contributing to national plans and strategies for sustainable development.

In addition to helping Member States develop their own facilities for plasma technology and accelerator utilization, the Agency can promote international cooperation in the use of major facilities that are too expensive for many countries to build, such as synchrotron radiation facilities and neutron spallation facilities. Expectations are that the use of plasma and accelerator technologies will expand in the next decade, and greater cooperation will be required for more countries to benefit from the range of applications. ❑

Photo: An electron beam accelerator at the University of Miami/Jackson Memorial Medical Center is designed for disinfecting infectious hospital waste.