

PP

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE

CA

CERN AC 93-04 BLIT
SW 9412



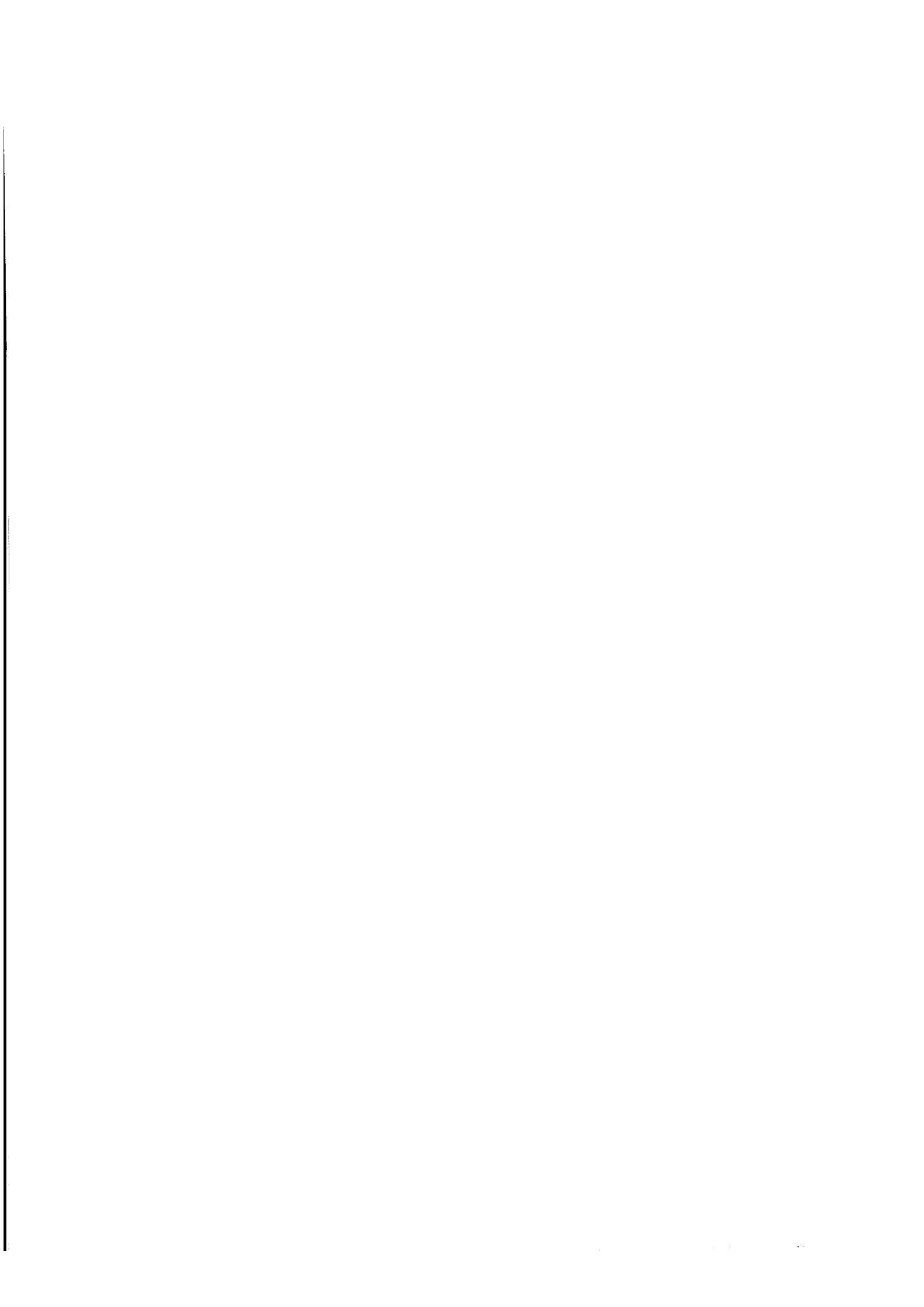
CERN/AC/93-04 (BLIT)/Rev.

APPLICATIONS OF PARTICLE ACCELERATORS

O. Barbalat

Prepared for the ICFA Panel on
Spin-Off from Particle Physics

February, 1994



1. INTRODUCTION AND OVERVIEW

The particle accelerator is one of the most versatile instruments designed by physicists. From its inception, as the cathode ray tube by J.J. Thomson who used it to study the properties of the electron, to the present giant colliders, it is intimately associated with the major discoveries in of nuclear and particle physics.

Today it is widely used in nearly every field of physics from elementary particles to solid state. It is also an essential instrument in many other areas of research to study structures in chemistry and biology or to perform sensitive trace element analysis. Its range of application is being considerably extended by its capability of generating synchrotron radiation and spallation neutrons. Progress in nuclear and particle physics originated from studies with accelerators is now playing a major role in astrophysics and cosmology.

Industrial applications cover a broad range of techniques such as ion implantation in the semiconductor industry and the modification of surface properties of many materials.

Radiation is being used in a variety of processes to preserve food, sterilize toxic wastes or polymerize plastics. Activation methods with compact accelerator produced neutrons are applied in geophysics and are being developed for the detection of explosives and for the general purpose inspection of goods.

It is probably in medicine that accelerators have found their widest field of applications, either for isotope production for diagnostic or treatment purposes or for therapy with gamma rays, electrons and more recently with neutrons and heavy charged particles.

In the nearby future, accelerators could play a key role in power engineering. Studies of inertial confinement fusion by heavy ions are actively pursued in several countries. Accelerators are an essential ingredient to provide the additional heating needed for plasma ignition in magnetically confined tokomaks. A concept for large scale accelerator driven energy generation from Thorium has recently been proposed. Finally research is also going on to use accelerators to incinerate long-life

nuclear waste (actinides) which could lead to an acceptable long-term disposal solution.

When discussing the application of particle accelerators, one should also mention the technical and industrial evolution induced by these applications. Whereas the front line machines are usually general purpose facilities designed for fundamental physics research such as particle or nuclear physics, these machines may later find a new life in more applied research fields such as solid state or material science. They are then followed by dedicated facilities for a more specialised type of research or process (synchrotron radiation, pulsed neutron generation, isotope production) and finally by single purpose optimized devices such as soft X-ray generators for microlithography, compact cyclotrons for positron emitting isotope production, ion implanters or radiotherapy electron accelerators. They are then produced on an industrial basis rather than designed and built by or for a research laboratory.

2. RESEARCH APPLICATIONS

2.1. Particle physics

The development of particle physics has been directly determined by the progress achieved in building accelerators of ever increasing energy. One can easily recall examples, such as the discovery of the antiproton at the Berkeley Bevatron in the mid-fifties, the two neutrinos with the AGS in the early sixties, neutral currents at CERN with the CERN PS, the J/ψ at BNL and Stanford with the AGS and the Stanford Linear Accelerator in the seventies. More recently, the W and Z with the Sp \bar{p} S collider and the number of neutrinos with LEP and the SLC are a clear demonstration of the continuing importance of accelerators to get a better and deeper insight to the structure and properties of the building blocks of matter, the quarks and leptons, and in the forces by which they interact.

In about forty years, from 1959 to 1990, accelerators and colliders have allowed physicists to gain three order of magnitude from 10^{-15} to 10^{-18} m (corresponding to 100 GeV for the constituents in the centre-of-mass reference frame) in their quest for probing matter at an increasing finer scale. They can describe our complicated world with only three families of particles, each being constituted of two quarks and two leptons characterized

by the properties of charge, flavour and colour which are responsible for the electromagnetic, the weak and the strong interactions. Accelerators of the present generation have led to the discovery of the carriers of these interactions, the gluons and the intermediate vector bosons better known as W and Z particles.

A new facility for probing matter through electron-hadron collisions (HERA) has just been commissioned in Hamburg, while a very high energy machine, the LHC, is now under design at CERN in the hope of elucidating some of the many basic physics questions which are still open, while lower energy specialized devices such as τ -charm and B-factories are envisaged to study more specific areas.

2.2. Nuclear physics

Accelerators are the essential tool by which physicists have been able to probe the nucleus, determine its structure and behaviour. Depending on the properties of interest, one is using electron, proton and more recently heavy ion beams. The increase in available energy and intensity is also opening new opportunities.

In the past, nuclear physics research has been devoted to the study of the structure of individual nuclei, their excited states and the associated spectroscopy. Present areas of interest are for instance super-deformed nuclei with extremely high angular momenta or exotic nuclei far from the line of stability produced by facilities such as Isolde at CERN or GANIL. The availability of heavy ion machines, like the GSI facility in Darmstadt, allows to study the dynamics of nucleus-nucleus collisions, and the fragmentation of nuclei. Subnucleonic degrees of freedom of nuclei such as meson exchange currents are investigated with both electron and hadronic probes, hence the interest for the Kaon project in Canada. The study of nuclear matter under extreme conditions allows to investigate phenomena related to the composite nature of nucleons. It is in particular hoped to reach the phase transition from nucleous to quarks and gluons by accelerating lead ions in the CERN SPS and ultimately in the LHC.

Electromagnetic properties of nuclei are best studied with electron beams of high energy (~ 10 GeV) to reach spatial resolution of 0.1 fm.

A new generation of high intensity electron accelerators will allow to study the quark structure of nucleons and investigate how they combine into hadrons. A 4 GeV machine (CEBAF) is under construction in the U.S.A. and a 10 GeV is being discussed in Europe.

Beam cooling developed for the $p\bar{p}$ collider is opening up many possibilities in nuclear physics on machines like LEAR at CERN and on dedicated heavy ion storage rings operating in Germany and Scandinavia.

2.3. Cosmology and astrophysics

Accelerators are now becoming more and more complementary to telescopes. The universe originated in a hot Big Bang, temperature decreased with time and the increasing energy of accelerators and colliders allows the physicist to study experimentally processes closer to the origin of the universe. At temperatures equivalent to an energy of 100 GeV, which is where present machines allow observations, one is 10^{-10} second from this origin and it is possible to study the moment when W and Z particles acquired their mass and disappeared from the scene. Results obtained with accelerators have allowed to explain cosmic observations such as the Hydrogen/Helium ratio and to determine the number of neutrino families.

Astrophysics issues can also be settled with accelerators. For example the understanding of the synthesis of elements in stars (nucleo-synthesis) requires the determination of the rate and cross sections of nuclear reactions. A recent development is the need to use radioactive particles beams which are necessary to investigate some reactions. Their understanding could explain some not yet understood features of stellar burning and in particular aspects of the sun behaviour such as the eleven years solar cycle or major climatic changes like the onset of ice ages.

2.4. Atomic physics

The detailed behaviour of the complex multiparticle systems which constitute atoms and ions is still far from being understood and computable. A large amount of research is conducted in many institutions, although the total number of facilities has probably decreased from the 850 positive ions accelerators with energies below 33 MeV reported to exist in the early 1970's.

The following list of topics discussed at recent conferences illustrates this type of research :

- Mechanisms of atomic collisions and ionization processes (charge distribution and rotational properties of electron cloud during collisions).
- Correlations effects in atomic collisions.
- Study of highly excited atomic states produced during atomic collisions.
- Physics of highly ionized ions and of bare atoms.
- Charge exchange cross-sections of high velocity or even relativistic ions (electron capture and electron losses).
- X-rays produced by relativistic ion collisions.
- Quasi molecular states produced by nearly symmetric ion-atom collisions.
- Electron impact ionization processes and electron ion collisions (of particular interest for the study of both laboratory and astrophysical plasmas).
- Electron emission following fast ion impact on thin solid target (in view of quantitative analysis of surface contamination).
- Resonant transfer and excitation (RTE) in ion-atom collisions (effect due to the resonant capture of a target electron by the projectile ion and the subsequent excitation of that ion).
- Production of convoy electrons. (This term refers to the electrons ejected in ion-atom and ion-solid collisions closely matched in vector velocity to that of the incident ions).
- Precision ion energy loss in solids.
- Precision range distribution and electronic stopping power in solids.
- Study of molecular ions.

2.5. Condensed matter physics and material science

The main tools used by physicists to probe the structure and properties of matter in the solid state have for a long time been X-rays produced by conventional sources and neutrons generated by nuclear reactors.

This picture has changed dramatically over the last few years with the advent of new accelerator derived radiation sources synchrotron radiation now produced by dedicated electron machines and neutrons from spallation neutron sources. In addition ion beams are used in a variety of ways.

Many research fields have been opened up or offered new prospects by the availability of synchrotron radiation with its brightness and tunability. The tunability of synchrotron radiation makes it possible to exploit the fact that each element exhibits a sharp increase in absorption at certain wavelengths called absorption edges. This is used to obtain information on the local or long range structure of material. The technique called EXAFS (Extended X-ray Absorption Fine Structure) gives information on the atomic environment around a particular elemental constituent of a complex material. This is used to study atomic arrangements in many condensed matter systems such as catalysts, crystals, glasses and other amorphous materials, polymers, surface layers, thin films, etc.

Because of their absence of charge and their penetration ability, neutrons make excellent probes for the study of condensed matter. Neutron scattering allows to understand the bonding and cohesion of metals, semiconductors and insulators. Neutron diffraction is concerned with the structural arrangement of atomic particles in a material and the relation of this arrangement to its physical and chemical properties.

Energetic (500 MeV to 1 GeV) protons produce intense bursts of neutrons by spallation in a target which allows a substantial intensity improvement compared with nuclear reactors. Furthermore, the time structure of the beam provides the added advantage of low background because the source is off most of the time. Studies with spallation neutrons are complementary to those carried with synchrotron radiation on topics like crystallography, in particular for powders when single crystals cannot be grown, liquids and amorphous materials, surfaces and intermaterial interfaces (air-liquid, liquid-liquid and liquid-solid), polymers, thin films, membranes, measurements under shear flow, magnetic and electrical fields.

Ion beams are utilized in many complementary processes to determine the elemental composition of samples.

The main techniques are :

- Rutherford Backscattering (RBS)
- Proton Induced X-ray Emission (PIXE)
- Charged Particle Activation Analysis (CPAA) or Nuclear Reaction Analysis (NRA)

- Secondary Ionisation Mass Spectrometry (SIMS)
- Particle Desorption Mass Spectrometry (PDMS).

RBS and PIXE are well-established techniques, CPAA and NRA are newer. While RBS is well adapted to study heavy elements in a light substrate which is the case of semiconductor research (Si substrate), NRA is better adapted to study the behaviour of light elements in heavy substrates (metals) and finds therefore a natural field of application in metallurgy. It is being used in particular for understanding the structure and features of high T_c superconductors. It allows to characterize unambiguously what a sample really looks like and not what it was intended to be before the constituents were made to react.

Charged Particle Activation finds its field of application in two areas : ultra low concentrations and wear studies. It is applicable to most elements and allows to identify trace elements at the ppb (part per billion i.e. 10^{-9}) level. One can determine the effect of impurities, such as carbon, nitrogen or oxygen, in metals, monitor the elaboration process and detect low level contaminants. Ion beams are used in a wide energy range (1 to 45 MeV) allowing depth analysis ranging from microns to millimetres.

CPAA is also a sensitive and fast technique for wear studies (corrosion, erosion). One activates a thin surface layer and for suitable isotopes, the loss of activity will correspond to the loss of matter. The method was reported to be used to monitor on line industrial processes. It has also been applied to study the effect of pH on the corrosion rate in nuclear reactors.

The utilisation of small spot size ion beams, also called nuclear microprobes, in the scanning mode has transformed the PIXE technique from an analytical tool in an imaging device, which permits to obtain a map of the elements in the studied sample showing where they are distributed so that the device could be described as being a nuclear microscope.

The elemental map can be compared with the structure given by optical or electron microscope. A compromise must be found between resolution requiring a small spot size and sensitivity which is directly related to beam intensity. Hence the requirement of high brightness (which is however limited by the need not to destroy the sample). Recent progress has allowed to reduce the spot size down to the micron level.

Reported applications of this technique include the mapping of structures in multilayer semiconductor devices to monitor the manufacturing process, the study of high T_c superconductor compound structures, the analysis of weld failures,....

The combination of RBS (Rutherford BackScattering) which allows to determine the depth profile with PIXE can give a three dimensional picture of the element distribution in the sample.

Whereas with ion beam analysis, the accelerator is used to bombard the sample with ions and detect the induced atomic or nuclear processes, in accelerator mass spectrometry (AMS) the constituents of the sample are ionized, accelerated and identified by mass spectrometry.

The high sensitivity of AMS finds applications in the semiconductor industry. Semiconductor devices are rapidly degraded by even small concentration of some impurities which can be readily detected by AMS. Up to now this was essentially studied by SIMS (Secondary Ion Mass Spectrometry). AMS gives a dramatic improvement of two orders of magnitude in sensitivity. The sample is ionized by a Cesium beam. Scanning of the sample by the Cesium beam allows imaging.

Another application of accelerators in material science is for radiation damage. It is of particular interest in studies of structural material for a future fusion power generator or for satellites and space systems.

2.6. Chemistry and biology

Accelerators are a source of radiation, in particular synchrotron light allows to get unique information on the chemical state (e.g. oxydation of molecules, the chemical bonding in solids, gases and absorbed layers, structure of complex molecules and their dynamics, kinetics of chemical reactions).

Electron accelerator with energies up to a few MeV are used in radiation chemistry studies, for instance the radiation enhanced chemical reactions of the highly active intermediate chemical states produced by the electron beam.

Radiation biology with accelerator has mainly been concerned with studies aiming at understanding the molecular pathways of radiation damage and with studies related to cancer therapy.

Synchrotron light has revolutionized many fields of biology. It is now possible because of the brightness and tunability of this source to study the crystallography of proteins and solve large structures like viruses, follow the structural changes of a molecule binding to an enzyme. It is possible to study the dynamics of biological processes for instance, study muscles under contraction with time frames of 10 ms.

The nuclear microprobes mentioned in the previous section find also applications in life science studies. Reported examples are the metal uptake of organisms, biomineralisation in teeth and bones, metal related diseases, element gradient in membranes, trace elements in neurological disorders (Alzheimer disease), etc.

3. ELEMENT ANALYSIS

The various accelerator laboratory techniques mentioned in the previous chapter for sample composition analysis and trace element detection are now extensively used in applied science, archeology, art or even for air travel security.

In geology and mineralogy one can proceed to elements zoning in rocks and minerals, determine the composition of inclusion and analyze grain boundaries. These techniques have also been used in the analysis of the structure of lunar material and meteorites.

Progress in geology has direct application to oil exploration and mineral research. A widely used technique in the oil industry is neutron well logging. Neutrons produced by the bombardment of a tritium target by deuterons activate the surrounding rocks. The gamma ray spectrum of the activated nuclei allows to determine the rock composition along the well and 'log' its profile.

For archeological dating with Carbon 14, accelerator mass spectrometry is used more and more instead of beta decay counting because of its much

greater sensitivity, hence the possibility of accurate dating with only a minute sample, i.e. a technique which for all practical purposes has become non-destructive. A noteworthy case has been the successful dating of the Turin Shroud with comparable results obtained in three different laboratories with a sample of only a few milligrams.

PIXE or Nuclear Reaction Activation Analysis is non-destructive and is used for studies of precious art objects. One has in this way been able to determine the composition of ancient jewels or of the pigment layers in old paintings. Pigment composition is a way to detect forgeries or additions to art-work, as old masters could not use the yet undiscovered organic compounds used in modern dyes.

A recent application is the possibility to detect concealed explosives. These substances are nitrogen rich and can therefore be detected by neutron activation. Compact accelerators for use in airports have been designed for this application. This technique is now extended for general purpose goods inspection to detect smuggling or fraudulent shipments at customs points or ports of entry.

4. MEDICINE

Accelerators are used in two broad ways in medicine for diagnostics and for therapy.

4.1. Medical diagnostics

Radio-isotopes have proved very early that they can give unique biochemical and physiological information when injected into living organisms. The possibility of external detection offers a non-invasive way to follow changes in the distribution of tagged atoms, observe anomalies of metabolism (changes in blood flow, oxygen utilization, glucose metabolism) or detect tumours.

Recently accelerator produced positron emitting radio-isotopes have been found to respond better to the needs of nuclear medicine than traditional gamma emitting nuclides in particular the widely used Technetium-99 (produced in nuclear reactors).

The annihilation radiation of positrons is easily detected and localized and has given rise to the growing field of Positron Emission Tomography (PET). Positron emitters are short lived and can be injected in human beings without giving rise to high radiation doses.

The production of these positron emitters is achieved by cyclotrons accelerating protons or deuterons in the 10 to 40 MeV range. The short half life of these nuclei requires them to be produced and utilized on the same site by dedicated facilities. Special purpose cyclotrons are now manufactured by industry and commercially available (Ion Beam Applications in Belgium or Scanditronix in Sweden), X in the US, Y in Japan.

Another technique is based on the high X-ray flux available from synchrotron radiation. The sensitivity to contrast agents such as iodine can be enhanced by two or more orders of magnitude by taking the difference between a pair of exposures with monochromatic X-ray beams, one just above, the other below the agent absorption edge. The increased sensitivity makes it possible to detect restriction in arteries by angiography without the invasive procedure of inserting a catheter in a major artery.

Finally one should mention the application of accelerator derived superconducting magnets to the fastly growing field of NMR imaging, a device which has become a powerful diagnostic tool superior in many respects to X-rays scanners. The availability of reliable and powerful magnets with small energy requirements and an already proven technology has been a decisive factor in the fast diffusion of this novel imaging technique.

4.2. Radiotherapy

It is estimated that 25 to 30% of the population of industrialized countries will contract cancer in their life-time and that about half of these will receive some form of radiation therapy. The aim of radiotherapy is to destroy the malignant cells without damaging the healthy tissues. Unfortunately, radiation travels in a straight line through the body and destroys cells in the entrance region between the surface and the tumour. Most kinds of radiation also have downstream effects, before exiting the body.

Unwanted damage to normal tissues is minimized by delivering the radiation from different directions crossing at the location of the tumour.

The vast majority of present facilities use X or gamma rays photons produced by ^{60}Co or by linear electron accelerators. Accelerators are more versatile and can provide deeper penetration when necessary. Five to twenty and even forty MeV machines are constructed industrially by several manufacturers : Siemens in Germany, CGR-MeV in France, Philips Medical Systems in Great Britain, Varian Associates in the US, Toshiba in Japan.

Major progress in cancer therapy is being achieved by improvement in the local control of the tumour. This is the result both of improved diagnostic tools which allow a better localisation of the malignant tissues and of the use of particle beams which permit a higher energy deposition (the characteristic parameter is the LET : Linear Energy Transfer) and a more accurate range.

Because of their high penetration and their biological effectiveness neutrons are for some cases more advantageous than photons. Neutrons are generated by the reaction of 200/300 keV deuterons on a tritium target. Large deuteron currents are needed to obtain sufficient fluxes resulting in rather short target life times. Furthermore, the neutron energy obtained in this way does not allow to treat deep seated tumours. One is therefore using classical cyclotrons with energies from 30 to 65 MV to produce fast neutrons by reaction on a beryllium target.

Pions, protons and heavier ions offer the possibility of improving the damage ratio between malignant tumours and healthy tissues. With heavy charged particles one can achieve a highly localized distribution. The so-called Bragg peak (region of maximum energy deposition) is only a few millimetres wide near the end of the range, which makes it possible to deliver a high dose with less damage to the overlaying and downstream tissues. The required penetration depth makes it necessary to use machines capable of producing particles in the several hundreds of MeV range. Present installations still have an experimental character and are located near accelerators built for another purpose (SIN, Bevalac, TRIUMF, Dubna,...) but dedicated therapeutical facilities are under design or construction. One should in particular mention the studies sponsored by

the European Community for a Light Ion Medical Accelerator Facility (EULIMA project). Heavy ions combine the advantages of high LET and precision penetration depth. Another feature is the possibility to combine therapy with treatment monitoring with the use of positron emitting ions which allow to check the adjustment of the beam by tomography .

The improvements in tumour control, morbidity reduction and restoration of individual quality of life, reported at recent conferences are a testimony to the contribution of accelerator technology to medicine.

In contrast with radiotherapy proper which involves radiation dose delivery to a substantial volume of tissue by a large number of daily treatments spread over several weeks, charged particle radiosurgery is a treatment of a well defined target, such as an intracranial lesion, with a narrow particle beam delivered in one or a few fractions. Various ions in the 100 to 500 MeV range are being used for that application.

5. INDUSTRIAL PROCESSING

5.1. Ion implantation

Ion implantation for manufacturing semiconductors is one of the major present industrial applications of particle accelerators. This process allows the introduction of ions of a specific type at the desired depth to dope in the appropriate way the semiconductor substrate and achieve the required circuit pattern. This technique has replaced the traditional ion diffusion used previously. It allows accurate and reproducible manufacturing of all the present compact micro-circuits.

The present generation of low and medium current implanters derive from physics laboratory devices with current of a few mA and voltages of a few hundred kV generated by multistage voltage multipliers. High current machines (say 300 mA) derive from the wartime calutron isotope separator. A major technical issue is the scanning either of the beam or of the target to achieve a tight control of the implant angle variations across the semiconductor wafer to achieve consistent electrical characteristics.

Present trend goes in the direction of higher energies produced either by electrostatic belt generators, RF linacs or RFQ's to achieve penetration

depths exceeding one micron. This gives the possibility to modify bulk properties and not only the surface or to produce buried patterns, synthesize locally and in depth oxides or silicides, so as to achieve truly three dimensional semiconductor circuits.

Ion implantation can also be used to modify other properties than electrical conductivity, the surface hardness, the corrosion resistance, the friction coefficient, the fatigue behaviour, the adhesive properties or the catalytic behaviour. Applications have been found in the automotive industry to improve the performance of highly stressed components (ball bearings, crankshafts, helicopter rotor shafts,....).

Other applications occur in the medical field where a spectacular increase in the lifetime of artificial joints (hip, knee,..) have been achieved and are now commercially successful.

5.2. Radiation processing

When passing through matter, particle beams cause excitation and ionization of the material. Charged and uncharged fragments of molecules resulting from bond breaking, have high chemical activity and tend to react quickly with one another or with other molecules. This opens the possibility to perform a variety of chemical processes.

Examples are :

- Polymerisation of low molecular components (monomers). The rate of polymerisation can be enhanced by a factor 100 compared with the process in a pure monomer.
- Radiation modification of wood to improve mechanical , fire or biological resistance.
- Radiation cross-linking of polymers to create three-dimensional structures to achieve for instance insolubility in organic solvents. This process is most extensively used with polyethylene pipes and insulated wires and cables operating in hard environment conditions (high temperature, aggressive chemical media, irradiation,....).
- Polyethylene cross-linking to achieve a 'memory' effect and obtain a thermo-shrinkable material used for tight packing of goods.

- Radiation vulcanisation of rubber to improve heat resistance and resistance to aging and deformation at high temperature. The effect is again obtained by cross-linking.
- Curing of varnish and paint coatings. Radiation processing acts in three ways by polymerisation of the monomers, cross-linking of the produced polymeric molecules and the development of chemical bonding between polymer and substrate.
- Fabrication of crease-resistant, fireproof hydrophobic textiles. This is the result of inducing polymerisation and cross-links and grafting water repellent compounds such as fluorinated acrylates or siloxanes on cotton or viscose rayon fibres.
- Destruction of noxious material by breaking down unwanted molecules. The industrial and domestic utilisation of surface-active synthetic agents (such as detergents) creates a serious sewage treatment problem since these products feature a high chemical stability. Radiation promotes their breaking into lighter and more easily removable substances. In the presence of oxygen, organic compounds are oxidized, which enhances the treatment effect.
- Purification of industrial gases. To clean gas containing sulphur or nitrogenous impurities one adds ammonia (NH_3). Irradiation initiates reactions of NO_x and SO_2 with NH_3 . The produced ammonia salts can then be trapped with an electrical precipitator.

These various applications have been particularly developed in the former Soviet Union by the Novosibirsk Institute of Nuclear Physics which manufactures a complete line of machines specifically designed to meet these industrial requirements.

5.3. Food preservation

Radiation sterilisation of foodstuff has a great economic potential. It allows to avoid the chemical additives now used for food preservation and which do meet increasing objections in view of their potential carcinogenic effects or to avoid the need to maintain at low temperature ready-to-serve meals.

One of the most promising application of radiation technology is sterilisation of culinary processed foodstuff which can after suitable packaging be stored at room temperature for several months. Successful

tests have been carried out with a large variety of foods such as smoked and fried sausages, ham, roasted potatoes, meat, chicken, filleted fish..... . The dose and energy must however be carefully adjusted to minimize the production of free radicals which in some cases may have unwanted side effects.

Another use of radiation is to suppress the activity of micro-organisms in fresh perishable food stuffs. Storage life of strawberries, cherries, peaches, grapes, tomatoes,... can be extended by 1 or 2 weeks. Unwanted germination of agricultural crops like potatoes or onions can also be prevented by radiation.

Radiation is also used for crop protection in storehouses against insects. The main method at present of insect control consists in the treatment of grain with chemicals, like methyl bromide or chloropicrin. This has the disadvantage, besides the high cost, of leaving toxic substances in the products. It has been demonstrated that with doses of 100 to 200 Gy most insects become sterile and die within 2 or 3 weeks while there is no measurable deterioration of wheat, maize, peas, rice or dried fruit.

Insect elimination by radiation is not only appropriate for food preservation in storerooms but has also been used for suppression of pests in natural conditions by releasing sterile males over large areas. Successful operation against certain types of flies have been reported in the United States, in Japan and more recently, on a wide scale in Africa.

5.4. Sterilisation

Industrial and domestic sewage sludge contain useful organic and inorganic substances which may be used as fertilizer in agriculture or as a nourishing additive to fodder. Special treatment for killing pathogenic micro-organisms is however required beforehand, which can be achieved by moderate radiation doses (30 Gy). This treatment can be combined with the destruction by radiation of deleterious chemicals mentioned in a previous section.

Radiation is also employed to sterilize medical products (garments, gloves,...) and to treat hospital waste products to ensure safe disposal.

5.5. Ion beam processing

Heavy ion accelerators are used to produce microporous membranes in thin film materials.

One can make holes ranging in diameter from 0,05 to 1 μm in membranes having a thickness of several tens of microns. The main applications are filters for the food industry and porous substrates for growing cells or micro-organisms for biology or medical research. Commercial companies have been set up and buy beam time on research accelerator to produce these membranes (Ganil, Louvain-la Neuve).

5.6. Microlithography

X-ray lithography with synchrotron radiation produced by electron accelerator is considered as a very strong contender for the production of the next generation of integrated circuits.

Present mass produced circuits are made by the photo-lithography process by which a master mask is projected onto the surface of a silicon wafer coated with a 'photoresist'. Present technology uses visible light which limits the resolution to around 1 micron. Resolution of 0.7 to 0.5 μm can be reached with strong lenses, but at the expense of depth of focus which raises serious problems of process control and yield. This is adequate for the present 4 MBit and 16 MBit memories which require a $\sim 0.5 \mu\text{m}$ line-width. However 64 MBit will require 0,35 μm and 256 MBit will need 0,2 μm . It is not entirely excluded that present techniques could be developed to that point but novel technologies shall certainly be required to reach the Gigabit range.

This explains the interest for X-ray lithography which allows a 0.1 μm resolution. Synchrotron radiation, because of its brightness, good collimation and capability to deliver the required power of the order of a kilowatt appears well suited for this application. Some ten machines in the 500 to 1000 MeV range, of which 6 in Japan, are under various construction stages in the world.

6. POWER ENGINEERING

6.1. Heavy ion fusion

The acceleration of heavy ions for fusion is one of the great challenge of accelerator physicists. Heavy ions to achieve inertial confinement offer several advantages over lasers which are currently studied for the same goal. The acceleration of ions can be achieved with a higher efficiency than producing the corresponding laser beam and with a higher repetition rate.

Heavy ions have a high specific deposition power in matter and the beam can easily be transported and focussed. A major problem is to achieve a symmetric implosion and one is therefore led to consider the so-called indirect drive whereby the kinetic energy of the beam is converted into radiation before imploding the pellet of material to be fused. Figures for inertial confinement fusion are pulses of 10 MJ of 10 nsec duration, with therefore instantaneous power of 10^{15} W over areas of the order of one cm^2 .

To achieve these values a considerable amount of R&D work is still necessary, but steady progress is reported at accelerator Conferences.

6.2. Plasma heating

It now appears that to achieve the required ignition temperatures and obtain an appreciable level of commercial power from a magnetically confined plasma, new methods of heating must be developed. One of the most attractive sources of additional power is the use of a multi-megawatt ion accelerator. The accelerator generates a negative ion beam which is neutralized in a gas or by photo-detachment, before crossing the confining magnetic field. It seems possible to reach the desired performance (~ 1 MeV/1-2 A) with an RFQ. Initially deuterium had been proposed, but heavier ions like oxygen appear more suitable.

6.3. Accelerator driven breeding and fission

Spallation neutrons generated by a proton accelerator could be used to convert a fertile material (^{232}Th or ^{238}U) into a fissile element. The target together with a suitable moderator can constitute a subcritical assembly

which generates energy when the neutron source, i.e. the accelerator is turned on. Recent progress in accelerator efficiency allows to expect an energy balance sufficient to make the concept economically attractive. As the system is not critical, it is intrinsically safe. A project based on the use of Thorium which has the additional advantage of producing only minute quantities of long life actinides and avoids the risk of weapon proliferation associated with Plutonium has recently been proposed.

6.4. Radioactive waste incineration

The possibility of using high energy accelerators for transmuting long life time radioactive waste from fission reactors into stable or short life isotopes is under investigation in several laboratories. Studies have been carried out at CERN in the early eighties with ^{90}Sr and ^{137}Cs using the 600 MeV beam of the synchro-cyclotron.

An ambitious Japanese project for the incineration of transuranium waste with high energy proton induced spallation reaction was presented at the last European Particle Accelerator Conference in Nice. One of the major problems of these incineration schemes has always been the energy balance. The process must not require a disproportionate amount of energy compared with the reactor production. The Japanese proposal is based on a 1.5 GeV proton linac with an average current of 10 mA.

The actinides transmutation target would be a subcritical sodium cooled assembly. The generated reaction energy would be recovered through a heat exchanger and a power plant to drive the accelerator. The facility could handle some 200 kg of actinide waste per year, corresponding to the production of about 8 reactors of a nominal capacity of 1000 MW with an efficiency of 50%, requiring therefore 30 MW. The proposed facility could generate excess energy for the electrical network. Another accelerator based incineration scheme is under study at Los Alamos

6.5. Other

The possibility of using muons, a type of heavy electrons produced by accelerators, has at one time been envisaged to catalyze thermonuclear fusion. Muonic atoms, because of the large muon mass, have smaller radii than normal atoms. Their probability to fuse is therefore higher and the

conditions for ignition easier to achieve. Unfortunately more detailed calculations have shown that the muon life-time is too short to achieve an overall positive energy balance.

Accelerator derived technologies, in particular in the field of superconductivity, may have a major impact in power engineering in the coming decades. Superconductors developed for high field accelerator magnets could be used for large scale magnetic energy storage of electricity. Superconductors have the potential of transporting large quantities of electricity in a compact cable compared with overhead lines. Superconducting alternators are under development. Commercial magneto-hydrodynamic or magnetically confined fusion generators would require efficient magnets and therefore have to use similar technologies.

7. CONCLUSION

In the hundred years following their first use to study the electron, particle accelerators have evolved into a wide variety of devices up to the giant colliders of particle physics. They have given rise to a multitude of applications, the most widespread being the television picture tube which is too familiar to be even worth mentioning. They now encompass most of the fields of physics research, play an essential role in medicine for both diagnostics and therapy, are used for many industrial processes and may, in the next century, offer possible technical answers to the energy problems of mankind.

Accelerator derived technologies are even more diverse, ranging to the already well established NMR imaging to novel methods of electricity generation, transport and large scale storage.

BIBLIOGRAPHY

- Applications of particle accelerators to particle physics as well as the corresponding physics results are regularly reported in the CERN Courier.
- Applications to physics in general together with discussion of new facilities and their research programmes are a regular feature of Europhysics News, the journal of the European Physics Society.
- Interaction between particle physics, astronomy and cosmology is the subject of the series of ESO-CERN Symposia.
- Applications in research and industry are extensively covered in the proceedings of the series of International Conferences on Applications of Accelerators in Research and Industry organized every second year in Denton, Texas, edited by J.L. Duggan and I.L. Morgan and published by North Holland.
- A series of European Conference on Accelerators in Applied Research and Technology (ECAART) have been organized since 1989. The most recent one took place in Orleans in September 1993. The proceedings are published by North Holland.
- Invited review papers on the applications of accelerators to industry and medicine have been prepared by K. Bethge and Y. Jongens respectively for the first European Particle Accelerator Conference (EPAC) held in Rome in June 1988 and are included in the proceedings published by World Scientific.
- Several papers on a variety of applications (synchrotron radiation for microlithography, radiotherapy, nuclear waste incineration, heavy ion fusion) were presented at the June 1990 EPAC, held in Nice and more recent work at the 1992 EPAC in Berlin.
- Information on medical applications of ion beams can be found in the proceedings of the Eulima Workshop on the Potential Value of Light Ion Therapy held in November 1988 in Nice, edited by P. Chauvel and A. Wambersie and published by the Centre Antoine Lacassagne of Nice.

- Industrial Electrons Accelerators and Applications are the subject of a book by E.A. Abramyan and published in 1988 by the Hemisphere Publishing Corporation.
- Particle accelerator applications are also well described in Particle Accelerators and their Uses by W. Scharf edited in 1986 by Harwood Academic Publishers.
- The Los Alamos concept for nuclear waste incineration is described in a paper by C.D. Bowman, published in Nuclear Instruments and Methods Vol. A 320 (1992) p. 336-367.
A review of the subject has been made by H. Lengeler at the 1992 CERN Accelerator School (report CERN/AT/93-02).
- Nuclear energy production driven by a particle beam accelerator based on Thorium breeding is described in a report by F. Carminati and al. (CERN/AT/93-47(ET)).