13
Applications of accelerators

13.1 Introduction
The reader will perhaps be surprised to hear that there are about 10,000 accelerators in the world and the vast majority are not built to study the fundamental particles of matter but are put to more ‘practical’ purposes.

Table 13.1 is from a world-wide study by Scharf and Chomicki (1996) who list a total of 112 accelerators of more than 1 GeV. Only one-third of these are dedicated to high energy physics while the rest are mainly synchrotron light sources. There are a further 5000 accelerators of lower energy for medical purposes: radiotherapy, biomedical research, and isotope production. A comparable number is deployed in industry, mainly as ion implanters and for surface treatment. In fact, more than 99% of the world’s accelerators have been built for use outside the discipline of particle physics.

13.2 Industrial processes using accelerators
Electron beams create electron showers which degrade to lower energy, where they excite chemically active sites. These can break up biological molecules in an organism, rendering it innocuous, or promote new bonds which polymerize

<table>
<thead>
<tr>
<th>Category of accelerators</th>
<th>Number in use</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) High-energy accelerators of more than 1 GeV</td>
<td>112</td>
</tr>
<tr>
<td>Biomedical accelerators</td>
<td></td>
</tr>
<tr>
<td>(2) Radiotherapy</td>
<td>&gt;4000</td>
</tr>
<tr>
<td>(3) Research including biomedical research</td>
<td>800</td>
</tr>
<tr>
<td>(4) Medical radioisotope production</td>
<td>~200</td>
</tr>
<tr>
<td>(5) Accelerators in industry</td>
<td>~1500</td>
</tr>
<tr>
<td>(6) Ion implanters</td>
<td>&gt;2000</td>
</tr>
<tr>
<td>(7) Surface modification centres and research</td>
<td>~1000</td>
</tr>
<tr>
<td>(8) Synchrotron radiation sources</td>
<td>~50</td>
</tr>
<tr>
<td>Total in 1994</td>
<td>10,000</td>
</tr>
</tbody>
</table>
and harden plastics. A large number of industrial processes make use of electron beams; many everyday objects rely on electron beam hardening—among them are computer disks, shrink packaging, motor car tyres, cables, and plastic hot-water pipes. Table 13.2 lists these processes and the end products. The energy and intensity of the beams required vary greatly. The energy is usually determined by the depth of penetration required and ranges from surface treatment, needing only a few hundred keV, to treatment of bulk material, where a beam of several MeV is needed to penetrate tens of centimetres of material.

13.2.1 Sterilization

Particle beams may be used for applications that include disinfecting drinking water, treatment of solid wastes, removal of noxious substances, treatment of waste gases, medical sterilization, and preservation of food.

Sterilization of foodstuffs is still one of those issues which the general public finds difficult to accept, yet the potential benefits are impressive. Doses of a few hundred Gy will render most insect pests sterile and lead to their death within a few days (Fig. 13.1), preventing the deterioration of bulk grain, vegetables, and fruits. A dose of 200 Gy will arrest their germination. Cooked food can be stored almost indefinitely at room temperature if it is packed and irradiated with a few hundred Gy and less benign artificial preservatives are no longer needed.
There are also some sterilization processes where accelerators can be used without exciting public debate. The accelerator is an alternative to the autoclave to sterilize surgical instruments and laundry. Also the preservation of foodstuffs for animals and the production of fertilizers for crops are generally perceived to be sufficiently remote from human ingestion, at least as far as the effects of radiation are concerned. Another unquestionably benign use of radiation is in destroying the bacteria infesting the detritus of the operating theatre. Even the sludge of sewage could be usefully incorporated in some products after radiation to kill pathogenic micro-organisms, though recently public opinion has turned against this. The required dose is of the order of 10 kGy.

13.2.2 Doses

The doses required for the various applications span a large range. In Table 13.3 we see that the current and power requirements for medical purposes are very low but at the other end of the spectrum, disinfecting sewage and drinking water on a large scale require quite powerful installations. A 12 MeV accelerator to treat the drinking water for a town of 100 000 people would have to deliver a beam power of 600 kW.

13.2.3 Ion implantation in semiconductor manufacture

Most of the applications mentioned above use electrons, but simple DC accelerators are used in great numbers in industry to accelerate ion beams of low
Table 13.3 Dose requirements for various radiation effects (after M. R. Cleland)

<table>
<thead>
<tr>
<th>Radiation effect</th>
<th>Dose requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiography (film)</td>
<td>1.0–10.0 mGy (0.1–1.0 rad)</td>
</tr>
<tr>
<td>Human lethal dose ((L_D^{50}))</td>
<td>0.4–0.5 Gy (400–500 rad)</td>
</tr>
<tr>
<td>Sprout inhibition (potatoes, onions)</td>
<td>100–200 Gy (10–20 krad)</td>
</tr>
<tr>
<td>Potable water cleanup</td>
<td>250–500 Gy (25–50 krad)</td>
</tr>
<tr>
<td>Insect control (grains, fruits)</td>
<td>250–500 Gy (25–50 krad)</td>
</tr>
<tr>
<td>Waste water disinfecting</td>
<td>0.5–1 kGy (50–100 krad)</td>
</tr>
<tr>
<td>Fungi and mould control</td>
<td>1–3 kGy (100–300 krad)</td>
</tr>
<tr>
<td>Food spoilage bacteria</td>
<td>1–3 kGy (100–300 krad)</td>
</tr>
<tr>
<td>Municipal sludge disinfecting</td>
<td>3–10 kGy (300–100 krad)</td>
</tr>
<tr>
<td>Bacterial spore sterilization</td>
<td>10–30 kGy (1–3 Mrad)</td>
</tr>
<tr>
<td>Virus particle sterilization</td>
<td>1–30 kGy (1–3 Mrad)</td>
</tr>
<tr>
<td>Smoke scrubbing ((SO_2) and NO(_x))</td>
<td>10–30 kGy (1–3 Mrad)</td>
</tr>
<tr>
<td>Ageing of rayon pulp</td>
<td>10–30 kGy (1–3 Mrad)</td>
</tr>
<tr>
<td>Polymerization of monomers</td>
<td>10–50 kGy (1–5 Mrad)</td>
</tr>
<tr>
<td>Modification of polymers</td>
<td>50–250 kGy (5–25 Mrad)</td>
</tr>
<tr>
<td>Degradation of cellulose materials</td>
<td>100–500 kGy (10–50 Mrad)</td>
</tr>
<tr>
<td>Degradation of scrap Teflon(^\text{®})</td>
<td>0.5–1.5 MGy (50–150 Mrad)</td>
</tr>
</tbody>
</table>

Energy and are an essential tool in the manufacture of semiconductors. A typical semiconductor production process might contain 140 operations, of which 70 involve the implantation of ions in the crystal lattice of the semiconductor. The implantation of ions at specific lattice sites and the creation of defects is a highly developed technology. The depth of the implant is controlled by choosing the ion energy which is usually between \(2\) and \(600\) keV. The species of the ion is selected by standard mass analysis techniques. Similar methods are now applied for the manufacture of superconducting materials where implantation is used to ‘pin’ atomic planes.

13.2.4 Surface hardening with ions

Ions are also used for the surface treatment of metals in the engineering industry. Tungsten, chromium, titanium, tantalum, nitrogen, boron, and other ions may be implanted to harden the surface of steel components such as ball bearings and cutting tools (Fig. 13.2), and to avoid corrosion (Grob et al. 1996).

Unlike more conventional surface-hardening techniques with chemicals and high-temperature furnaces, ion beams do not heat the surface and further annealing is not required. The ions can be of metallurgically ‘forbidden’ atoms and can be implanted in a surface layer which will avoid subsequent fissures. Typical applications are in the manufacture of artificial hip and knee joints (Fig. 13.3) and in the manufacture of control and fuel rods for nuclear reactors. The density of implantation for hardening purposes is about 100 times that used in the manufacture of semiconductors and the accelerator must produce currents in the range of \(5–10\) mA at energies in the range \(50–200\) keV. The flux required for ion
Implantation is considerable and the number of ions which are deposited is in the range $10^{15}$–$10^{17}$. The latter number represents as much as 10% of a layer of material several thousand angstroms in thickness.

### 13.2.5 Precision machining and membrane manufacture

Ion beams may be used as precise tools for machining plastic surfaces to a depth which far exceeds the transverse dimensions of the surface features. In Fig. 13.4 we see how ion track etching is used to produce an extremely fine filter from a polymer foil. It is possible to make membranes with track diameters from 10 μm down to 10 nm and densities from 1 to $10^9$ pores per cm$^2$.

### 13.3 Types of accelerator used in industry

#### 13.3.1 Electrostatic single-stage accelerators

We start at the low-energy end of the spectrum. Many of the accelerators used in industry for surface treatment require only a low energy—often less than 750 keV.
Fig. 13.3 Hardening an artificial knee joint (courtesy of GSI photo).

Fig. 13.4 Filter micro-machined with ions (courtesy of GSI photo).
Fig. 13.5 Methods of surface treatment (after Scharf 1996).

Fig. 13.6 Sterilization of surgical supplies (CERN courier photo).
This can be achieved by a simple electrostatic accelerator. A DC potential is applied to a wire anode and electrons extracted through a slot in a co-axially mounted cylindrical cathode. Such a strip treatment setup is shown in Fig. 13.5. An alternative technique is where the beam emerging from a simple electrostatic accelerator is swept over the surface of a moving belt.

Where low intensity is needed and when the energy must be high enough to penetrate many grams of material, electron linear accelerators of a few MeV are often the preferred solution. We need an electron beam energy of 5–10 MeV to penetrate a significant thickness of material, say 20 cm of plastic. In Fig. 13.6 we see boxes of medical and surgical produce passing on a conveyor below the accelerator. The beam, descending vertically, is swept from side to side with an oscillating dipole to cover the target volume in the manner of Fig. 13.5. All of this must take place in a well-shielded vault separated from the outside world by chicanes (Fig. 13.7) (Drewell et al. 1996).

### 13.3.2 Ion accelerators

Ion sources usually involve the bombardment of a gas or vapour with electrons. Often the electrons come from an arc discharge between two electrodes and the ions emerge from a slit in a cathode aligned with the arc. Once through the slit, the beam is accelerated towards a larger hole in an extraction electrode. This beam must be neutralized with an ‘electron gas’ to minimize defocusing due to space-charge forces. Usually, the ion source must be at the positive high-voltage terminal of the accelerator so that the accelerated beam emerges at ground
13.3.3 Cockcroft–Walton and Dynamitron®

Linacs, although favoured for electrons in the 1–5 MeV range, become complicated if they are to accelerate particles of different charge-to-mass ratios at velocities below that of light. Protons or ions may be accelerated with Cockcroft–Walton or Dynamitron® accelerators to higher energies than are possible with a simple electrostatic gun. These machines can also be used to accelerate electrons. Figure 13.8 shows the principle of the Cockcroft–Walton circuit: a chain of diodes which alternate in polarity and are capacitively coupled to each other. A relatively modest alternating voltage, $V$, applied across the lower diode is multiplied by the number of the diodes in the chain. Each cell acts as a full-wave rectifier to the alternating voltage, and their DC voltages add up in series across an accelerating column.

The dynamitron (Fig. 13.9) uses a similar diode column but the alternating, r.f. potential is applied in parallel to each diode from a cylindrical capacitively coupled r.f. electrode. Such DC accelerators are filled with insulating SF$_6$ gas under pressure and large-dimension vessels separate the anode and cathode.

13.3.4 van de Graaff accelerators

Although Cockcroft–Walton and Dynamitron® accelerators are used extensively up to a few MeV, a different kind of DC machine, invented by van de Graaff in the early 1930s, takes over above this energy and may be used up to about 15 MeV. In a van de Graaff accelerator, a moving belt transports charge to a high-voltage terminal, which forms one end of an accelerating column. In a tandem configuration, negative ions produced by adding loosely bound electrons...
to the neutral atom, may be accelerated from ground to a positive terminal, stripped, and further accelerated as positively charged ions towards a ground potential. This principle doubles the energy of the emerging beam for any given terminal voltage. The pressure vessel is often filled with SF and the current is typically in the range 0–100 μA. In Fig. 13.10 we see a horizontally mounted van de Graaff machine from which two spectrometer arms emerge. This particular setup is used to activate trace elements in a sample and identify the elements from their reaction products analysed in a mass spectrometer.

13.4 Medical applications

13.4.1 Isotope production

Accelerators, mainly cyclotrons, produce about 20% of the radio-pharmaceutical materials injected into patients and about 35 of the 200 of the world-wide inventory of cyclotrons are used for this purpose. Typically, these cyclotrons accelerate protons in an energy range up to 40 MeV in beams of 50–400 μA. They must be designed to be compact, reliable, and to produce high-intensity extracted beams with a minimum of human intervention (Bechtold 1996; Lewis 1996). Remote handling of the targets is essential at these intensities and must ensure a
speedy transfer into the often automated procedure for radiochemical extraction, dispensing, labelling, packaging, and delivery of short-lived products.

The isotopes commonly have a half-life of about three days. When injected, their activity should be low enough to keep the effective dose below 5 mSv (0.5 rad) yet provide diagnostic information with optimal $\gamma$-ray imaging in a 15-30 min session.

### 13.4.2 Positron emission tomography

This diagnostic technique uses short-lived isotopes in conjunction with imaging systems based on particle detection techniques. The isotopes emit positrons, which are detected as back-to-back $\gamma$'s and which may be projected back to locate the emission point. The isotopes can be incorporated into biochemical
molecules which find their way to particular sites in the body, revealing a three-dimensional picture of biochemical activity. So short is the half-life of these positron emitters (~20 min) that the small cyclotron which produces them and the automated synthesis system have to be installed in the room next to the patient.

13.4.3 Therapy

In the past, radiotherapy made extensive use of radium needles or 2 MeV \( \gamma \)-rays from cobalt ‘bombs’. Electron linear accelerators in the range of 15–20 MeV are currently used to produce X-rays to reach deep tumours (Gahbauer and Wambersie 1996). The beams must converge on the tumour from several directions if healthy tissue is to be spared. The margin between a dose sufficient to destroy malignant cells and that low enough to allow healthy tissue to regenerate is only 10% or 20%.

13.4.4 Proton therapy

Attempts to spare intervening tissues are not helped by the exponential decay of X-ray intensity as it penetrates the body (Wilson 1946). Protons offer a better solution since they deposit most of their energy in a sharp ‘Bragg’ peak, leaving intervening tissue relatively unharmed and completely sparing sensitive organs just beyond the tumour site (Sisteron 1996).

The ideal energy for protons is 200 MeV, sufficient to reach any internal organ. Proton synchrotrons have been constructed for this purpose notably at Loma Linda, PSI, San Diego, USA, and HIMAC in Japan. Others are planned and the alternative of a superconducting cyclotron has led to new projects in Massachusetts, USA, and NAC, South Africa. Cyclotrons with their continuous beam of small emittance enable very precise control of dose and treatment zone.

13.4.5 Ion therapy

Recent research into the density of ionization as ions pass through cells suggests that ions are better suited than protons in ‘taking out’ large sections of DNA which cannot regenerate. Trials to verify this in a chemical situation are underway at LBL, Berkeley, and HIMAC, Japan. Other synchrotron projects which include the light-ion option are planned at GSI, Darmstadt, and TERA in Italy.

13.4.6 Beam delivery

Millimetre precision is often needed to confine the dose to the tumour. The beam energy may be modulated with a rotating disc of absorber of varying thickness and the beam shape defined by fixed or movable leaf collimators. In the simpler systems, the irradiated zone is made to conform to the tumour by directing the beam from one side, then the other, and also perhaps from above. Complex gantries have been built which direct a horizontal beam from the axis of
a rotating wheel structure to the rim and then in, towards the patient at the turn of the structure. These are favoured by proton therapy centres but represent a large fraction of the cost of the facility. Gantry for ion beams are more difficult because of the large emittance and magnetic rigidity.

13.5 Research applications

13.5.1 The high-energy frontier

We are all very familiar with the use of high-energy lepton and hadron colliders for particle physics. The essential questions under study include the search for the Higgs particle thought to be the origin of mass, the stability of protons, and the mass of neutrinos. At the time of writing, accelerator builders are considering using muon storage rings as a precise source of neutrinos as an alternative to solar and atmospheric neutrinos. All this research has an intimate relation with astrophysics and cosmology in re-creating the particles and interactions which prevailed just after the Big Bang and before nuclei were formed from more fundamental particles. The data are essential in simulating cosmological models and to help us understand the mystery of the missing mass in the universe.

13.5.2 Nuclear physics

Equally important, but a little later in the chain of events of creation, are the measurement of interactions of protons, neutrons, and the nuclei as they began to condense out from the primordial soup. Much of this information came, and is still coming, from nuclear physics research with the low-energy van de Graaff accelerators and cyclotrons, which were developed in the early days before and after the Second World War. More recently, heavy ions have been used to probe nuclear structures with the techniques of spectroscopy. Modern research focuses upon nuclei which are unstable and lie far from the mainstream of stable nuclides or which are anomalous in other respects such as superdeformed nuclei with very high-angular momentum.

The availability of ion beams enables us to study nucleus–nucleus collisions, and, with the aid of beams of both high energy and intensity the meson change and quark structure of nucleons—work that is now actively being pursued at CERN’s Isolde and at Ganil in France. Returning to even higher energy, there is evidence that CERN’s heavy-ion source combined with the SPS collider have been able to establish the conditions in which nucleons dissociate into gluons and quark plasma. Such research will be a principle activity for RHIC at Brookhaven Laboratory and RIKEN in Japan.

13.5.3 Techniques for the analysis of materials with particle beams

The analysis of small samples of material is an essential requirement in many fields of research and can prove useful in fields unrelated to science. Examples
range from the dating of archaeological objects such as the Turin shroud, or sequencing Galileo’s manuscripts to the detection of explosives and contraband in freight cargoes rolling through the entrance to tunnels. The techniques (Bethge 1993; 1996a,b) are too numerous to describe in detail, but we list some of the more important methods below.

13.5.3.1 Rutherford Backscattering (RBS)
Rutherford backscattering is a technique in which the energy of ions is measured as they are backscattered from a sample by Coulomb interaction. Peaks in the spectrum are a sensitive indicator of particular target nuclei. The cross section is in fact proportional to the $Z^2$ of the sample. The sensitivity is quite phenomenal and can be as high as 0.1 ppm. A typical probe beam consists of He$^+$ ions at 2 MeV per charge. The penetration depth, even for these light ions, is only a few microns but heavier ions may be used to improve resolution when thin films are under study. Higher-energy H$^{++}$ ions (4 MeV) can be scattered by the nuclear potential to exhibit resonances which are characteristic of the target nucleus.

13.5.3.2 Particle-Induced X-Ray Emission (PIXE)
In this technique, an ion beam, often protons, is used to excite target atoms so that they emit characteristic X-rays. The method probes a bulk sample but may be made to have high lateral resolution by focusing the incident beam down to a few microns and enabling high-resolution maps of the surface composition to be made and later compared with electron micrographs (Baglin et al. 1996). Like RBS, its sensitivity may be as high as 0.1 ppm. To achieve both high resolution and sensitivity, the brightness of the particle beam is crucial. The extreme sensitivity of this technique with its non-destructive character leads to its popularity for detecting anachronistic chemicals in ‘ancient’ artefacts.

13.5.3.3 Nuclear Reaction Analysis (NRA)
A general class of analytic methods makes use of narrow resonances in the cross section of the reaction of the accelerated particles with different nuclei. A large body of data tabulating these resonances grew up as accelerator beams were used to probe nuclei, and now the more striking features can be used to identify many specific constituent nuclei. Typically, scattering of α particles shows a sudden enhancement at 3.045 MeV when $^{16}$O is present in the sample. This is a technique that lends itself to heavy-metallic substrates and is much used in investigating high-$T_c$ superconductors.

13.5.3.4 Elastic Recoil Detection (ERD)
In a technique which complements RBS, one observes the recoil of the heavy target nucleus. It is a well-known feature of the kinematics of such scattering that the recoiling nucleus is scattered with a distribution which becomes more
restricted in angle as the mass of the nucleus increases. Alternatively, the time of flight (energy) of the recoil particle can be used to determine its nature.

13.5.3.5 Charged Particle Activation Analysis (CPAA)
This is the most sensitive of the activation analysis methods (1 ppb) for elements like boron, carbon, nitrogen, and oxygen, whose unstable isotopes are positron emitters. Samples are irradiated for times of the order of several half-lives and then, from the decay curves of the various excited nuclei, one may extrapolate back to determine the relative composition at the time of irradiation. The sensitivity of this method lends itself to the study of wear and corrosion. This technique is used to screen luggage and other goods in transit for explosives or drugs.

13.5.3.6 Accelerated Mass Spectroscopy (AMS)
An even more sensitive method ($10^{-14}$) for relative abundance of isotopes consists in accelerating sample particles in a beam, stripping to remove contamination, and then using momentum analysis to separate the spectrum of masses. Only very small quantities of material need to be sacrificed and the method is particularly appropriate for C\textsuperscript{12}, C\textsuperscript{14} separation in age determination, replacing the earlier $\beta$ decay counting method (Jianjun et al. 1996). Recent years have seen AMS used extensively in archaeology and in the history of art.

13.5.3.7 Extended X-ray Absorption Fine Structure (EXAFS)
This is a technique that makes use of a monochromator to select and tune the wavelength of synchrotron radiation. The resolution can be as small as 1 eV in a spectrum of 10 keV. As the wavelength of the radiation is scanned, sharp rising edges appear in the absorption spectrum as the energy threshold to excite, for example, the electrons in the K shell of an atom, is reached. The technique is sensitive enough not only to analyse the atomic and molecular constituents in a material but also to deduce interatomic distances. It is extensively used in research into the production of catalysts and the structure of the molecules of biochemistry.

13.5.4 Techniques for revealing the structure of crystals and molecules

13.5.4.1 Diffraction
Revealing the repetitive structure of a crystal by observing the diffraction pattern produced when it is illuminated with monochromatic waves is a basic experimental technique of physics. Much of today’s rapid progress in understanding the structure of materials and the composition and shape of the many complicated biochemical molecules that control our bodies’ development and health results from diffraction studies (Mutsaers et al. 1996).
The more detail we seek, the shorter the wavelength of the probe, whether it is a photon or neutron. Synchrotron light and neutron beams, having wavelengths many orders of magnitude less than visible light, have become powerful probes for this work. Accelerators to produce these probes are either electron synchrotrons of a few GeV dedicated to produce synchrotron radiation, or proton synchrotrons whose intense beams of a few hundred MeV produce neutrons when they hit a metal target—a process referred to as spallation.

The ordered pattern of a crystal can act like a three-dimensional diffraction grating producing a pattern which, when analysed, contains the information necessary to reconstruct the scattering object’s shape. If the radiation is strong enough, amorphous samples can also be used. Here one relies on the fact that the few crystals which subtend the Bragg angle between the source and the observer contribute to the pattern, rather as the rain drops make a rainbow. Of course, the random orientation of the target results in circular haloes rather than the clear spots that crystals produce, but these can be disentangled. Molecules, such as proteins and viruses, are studied in this way as are the repetitive structures in polymers and other large molecules. Synchrotron light and neutron beams are used for today’s scattering experiments.

As these tasks become more challenging, brighter sources of radiation are needed, but eventually there comes a point where the object to be studied is too small to have repetitive features. It is then that one must turn to X-ray spectroscopy and, in particular, EXAFS described above, by which the interaction of the electron with its surrounding atoms may be revealed. This has been used to study such materials as catalysts and surface layers on industrial glass. Only synchrotron light sources may be used for this. Neutrons do not interact with the electronic structure of atoms.

As just one example of such research techniques applied to the development of new polymers, Boeing replaced aluminium with glass-filled poly-ether–ether–ketone resin developed through synchrotron light research which allowed them to reduce the weight of a Boeing 757 by 30%.

The list of fields of research and application for synchrotron light and neutrons is impressive (Table 13.4).

### 13.5.5 Synchrotron radiation sources

Electrons circulating at high energy in a synchrotron or storage ring emit a tangential beam of synchrotron radiation over a wide range of frequencies from visible wavelengths into the X-ray region. Many electron rings in the energy range from 1.5 to 8 GeV have been built to serve a number of experiments arranged around their circumference with beams of synchrotron light. One of the largest is the 6 GeV machine, the ESRF at Grenoble. Wiggler magnets and undulators, placed at the point of emergence, enhance the brilliance of the cone of radiation, and monochromators are used to select narrow bands of wavelength where required.
Table 13.4 Fields of structure research

| Crystal structure with large cells (proteins and enzymes) |
| Lattice dynamics |
| Phase transitions |
| Diffusion in solids |
| Metal-$H$ systems |
| Interfaces—bonding between semiconductors + insulation |
| High $T_c$ materials |
| Magnetic materials |
| Polymers |
| Defect structures (stress and fatigue) |
| Fullerenes |
| Liquids and quantum liquids |
| Soft matter |

The many users who gather around the perimeter of these machines come and go much more frequently than their high-energy physics colleagues. They may be research workers in fields as diverse as the study of the structure of materials such as the hardening of ceramics, or molecular biologists interested in the structure of HIV protein or the SV4D virus, known to induce tumours. This science of designing molecules to modify protein behaviour with new drugs and configure enzymes to promote industrial processes is a rapidly growing field in which experiments using synchrotron light play a crucial role.

Another industrial use of synchrotron light, yet to be fully exploited, is X-ray lithography (Basrour et al. 1996). A pattern created on a mask is transferred by X-rays onto a wafer coated with photoresist, which is then developed and the surface etched away, allowing semiconducting circuits to be produced with even greater precision than the conventional UV etching. The nominal present-day precision of 0.5 μm can be reduced by a factor of 5, leading to even faster and compact computer chips. In Fig. 13.11 we see a portable synchrotron light source built for IBM and in Fig. 13.12 the principle of lithography.

13.5.6 Spallation sources

Neutron beams complement synchrotron light as probes for the study of condensed matter and molecular structure. Although comparable in wavelength, the intensity and brightness of neutron sources for scattering studies cannot compare with synchrotron radiation. However, neutron beams penetrate deep into bulk materials and interact principally with nuclei, while the electromagnetic interaction of synchrotron radiation is mainly with atomic electrons. One advantage of neutrons is that their weak interaction results in much less damage in the study of biological material. Another is that when their wavelength is matched to the dimension of the cells of a crystal their energy is comparable to that of the elastic modes within the crystal. This is not the case for synchrotron radiation.

High-flux reactors provide fluxes of neutrons as high as $10^{15}$ neutrons cm$^{-2}$ s$^{-1}$, but at the cost of very high power densities in the reactor core. In a fast neutron
Fig. 13.11 Helios (CERN courier photo).

Fig. 13.12 Principle of lithography.

beam from a high-flux reactor, the wavelength is selected with a monochromator, and inevitably the flux is wasted.

Only about one-fifth of the energy is involved when neutrons are produced from a 1 GeV proton from a spallation source. The average number of neutrons
produced is about 25 and they must be slowed down with a hydrogen-rich moderator, from which they emerge as a white spectrum.

The beam from a synchrotron is pulsed, typically a short (<1 μs) burst every 20 ms. Over a flight path of 20 m, fast neutrons of wavelengths between 0.1 and 0.4 nm arrive at the detector spread over a 20 ms interval and may be resolved with a time (wavelength) precision of 1/2000. Whatever the accelerator used as a source, the mean current is of paramount importance. This translates to power (between 0.1 and 5 MW) delivered to the target. Spallation sources produce a peak power in the pulse which exceeds that expected from a reactor.

Spallation sources under study hope to raise the power from 160 kW (world record, presently held by ISIS) to 1 MW (ANC, SNS LAMPF, and AUSTRON), and the ambitious ESS in Europe which aims for 5 MW. ESS injects ~600 turns directly from a 1.33 GeV linac into each of two accumulator rings (Lengeler 1990). The beam from each ring is extracted directly after the other to produce the pulse on the target. These projects use H− linacs with fast stripping injection schemes. In order to inject many turns, vertical orbit bumps and the effect of horizontal displacement are used to fill the phase space in the transverse plane. Dispersion coupled via Δp/p fills the longitudinal phase space. SNS will inject 1200 injection turns into a single ring using both vertical and horizontal bumps. The Japanese project JHF aims at 2700 turns.

13.6 Heavy-ion fusion

It is, of course, everyone’s dream to produce energy by fusion and, as a first step, to demonstrate ‘ignition’ at the Lawson criterion

\[ n\tau \approx 10^{15} \text{cm}^{-3} \text{s}, \]

where \( n \) is the density and \( \tau \) the confinement time. Firstly magnetic confinement, then lasers, and finally the beams of heavy ions have been considered as a means to achieve this. In the case of ions, as with lasers, first ideas—the so-called direct method—envisaged a large number of beams hitting a tiny pellet of frozen deuterium–tritium ‘fuel’ from all sides. It turns out that the synchronization and uniformity of the beam distribution required is critical and, in modern ‘indirect-drive’ methods, ion beams coming from two or more sides convert their energy into X-rays which, within a casing acting as a ‘Hohlraum’ or black body enclosure, transfer the impact energy uniformly to the pellet (Fig. 13.13) (Hofmann 1996).

The topology of an accelerator complex required to do this is, nevertheless, formidable. In Fig. 13.14 we see a 10 GeV linear heavy-ion accelerator, fed by 16 ion sources of three distinct species of ions which pass through four funnelling stages of RFQs. The 10 GeV ions are stored in 12 storage rings (Prior 1998). Each ring contains 12 bunches which are unloaded and synchronized before acceleration in six induction linacs.

To further improve current concentration, the six induction linacs unload simultaneously from quadrants, the path length to the target being made equal rather like the exhaust manifold of a high-performance racing car. The final
energy and the three likely candidates of heavy ions (Bi, Th, and Rh) are selected so that their different masses allow them to catch up at the target. The space-charge forces, which threaten to defocus the beam in the last few metres as it
converges on the target, argue for the highest possible energy while the requirement that the ions deposit all their energy within the small thickness of the pellet assembly requires that the energy is low enough to lie high on the steep side of the energy loss versus energy curve. The compromise is much easier to achieve for heavy ions. At each stage, the limits of accelerator technology are challenged.

13.7 Waste transmutation and the energy amplifier

The hope of obtaining limitless electricity from nuclear power has been dampened in the last few decades by the realization that power stations generate a legacy of poisonous actinides with half-lives which are long on a geological scale and that accidents in the reactor and in the waste processing and storage industry are, in the public’s perception, rather likely. One of the solutions proposed for dealing with the nuclear waste from power stations is to use a high-current proton beam to convert long-lived nuclides into others which are either stable, short-lived, or which may be used as fuel again. Such proposals have been made by a Los Alamos group, whose high-current LAMPF proton linear accelerator comes closest to the currents required. The viability of the proposal depends upon the cost of the linac and the power required to run it, but it is argued that this will always be much more than the cost of doing nothing and just storing the material underground.

The energy amplifier (Rubbia 1996) offers a means to eliminate this waste, but at the same time produces power on a scale which pays for its capital and running costs (Fig. 13.15). This is an application of accelerators which, if it comes to pass, might affect the prosperity and way of life in the developing world as much as in industrialized countries.

Many of the fears of nuclear power experienced by the general public may be drastically reduced if thorium rather than uranium is used for power production. The waste is a much more benign list of nuclides with lifetimes shorter than the 700 years used as a benchmark. Thorium is plentiful and can be burnt in its natural form requiring no separation. It may be assembled into a reactor which is both stable and sub-critical, depending for its supply of neutrons on a 1 GeV proton beam of about 10 mA current. The term ‘energy amplifier’ refers to the ratio of output power to that required to operate the accelerator. Clearly, the aim is to make this as large as possible and the challenge is to build a high-current accelerator system which converts as much of its wall-plug power into beam power as possible.

If the ratio of beam power to that drawn from the mains is small, the overall amplification becomes rapidly uneconomical. The choice of accelerator system is evidently crucial. Linacs have been considered but proponents now favour a chain of cyclotrons. The energy required, 1 GeV, is within the range of cyclotrons and, although these accelerators tend to involve a bulky and expensive magnet system, they can run continuously. Modern high-current cyclotrons, PSI, TRIUMF, etc., approach the required current.
Applications of accelerators

Fig. 13.15 The energy amplifier.

Fig. 13.16 The driver for the energy amplifier.
These modern cyclotron systems (Fig. 13.16) are very different from the simple machines built by Lawrence in the 1930s (Mandrillon et al. 1996). Their magnets are split into a number of C-shaped sectors between which there is room to interpose enough r.f. acceleration cavities to keep the turns separated. The entrance and exit faces of the poles of the magnet sectors are curved to provide a constant amount of alternating or ‘ridge’ focusing per turn. This extra focusing decouples us from the need to have a weaker integrated field at large radii and one can actually increase the field with radius to maintain isochronism as relativity destroys the classical invariance of revolution frequency. Complete turn separation means that the beam may be extracted without destroying the septum deflector which is the essential element in the extraction system. Beam loss is minimal and the transmission efficiency of the accelerator is close to 100%.

Space-charge forces in the transverse and longitudinal planes disturb this focusing and modify bunch length, energy spread, and emittance. For this reason we cascade a chain of cyclotrons, the smaller ones with parameters chosen to combat the space-charge forces. In the scheme currently proposed for the energy amplifier, the first level is a pair of cyclotrons each fed by its own proton source and RFQ. The second level of cyclotron has relatively straight sectors appropriate to its non-relativistic energy range. The last machine with many curved sectors brings the beam to 1.0 GeV.

A pilot project is now about to be launched, intended to stimulate the industry to go into mass production.

**Exercises**

13.1 An electron beam of 2 MeV and a mean current of 5 mA passes through a 2 mm thick plastic ribbon. The beam width is 15 cm and the ribbon (density $1.4 \, \text{g/cm}^3$, $dE/dx = 2.1 \, \text{MeV/(g cm}^{-2})$ travels at 80 cm/min. Calculate the beam intensity in electrons per second and the total beam power.

13.2 Calculate the area swept per second and the power deposited in the film.

13.3 Calculate the mass of material irradiated per second and the dose received in kGy (1 kGy = 1 kw s kg$^{-1}$).

13.4 Synchrotron light of 1 A is a useful probe for molecular structure. Compare its resolving power with the scale of crystal structure, DNA, organic molecules (benzene), simple atoms, and nuclei.

13.5 What energy neutrons give a comparable resolution to a synchrotron light of 1 A?

13.6 Compare a high neutron flux reactor ($10^{15} \, \text{neutrons cm}^{-2} \, \text{s}^{-1}$) with the intensity of a typical spallation beam of 0.4 MW at 1 GeV protons producing 25 neutrons per proton at a pulse rate of 50 Hz.