PART 2—Aarhus University, Seminars on advanced Technology arising from General Accelerator Physics

ADVANCED TECHNOLOGY AND APPLICATIONS ARISING FROM PARTICLE PHYSICS

O. Barbalat
CERN, Geneva, Switzerland

ABSTRACT
In order to build accelerators and detectors, particle physics uses a variety of advanced techniques in the field of heavy and light mechanical and electrical engineering, vacuum, surface and material sciences, electronics and computing. It has often prompted new developments in order to enhance their performance. Particle accelerators which are the main tool of the particle physicists have now numerous applications in the industrial and medical fields. Particle accelerators are also at the origin of new sources of high quality radiation. These techniques are reviewed with particular emphasis on already commercial or potential applications in other fields.

1. INTRODUCTION

The study of the basic constituents of matter, now called High Energy Physics or more appropriately Particle Physics has a long history of technical spin-off. Before considering present day advanced technologies arising from this field of research it is not irrelevant to consider a few examples from a more distant past which, because of the larger time span, may give a better idea of the technological wealth originating from fundamental research.

In the second half of the 19th century physicists, who were trying to understand the nature of electricity, investigated at length the phenomena associated with the electrical discharge in rarefied gases. An outcome of this research was the discovery that the negative electrode, also called cathode, was emitting rays which are known to-day to be electrons. This discovery is at the origin of the ubiquitous cathode ray tube (CRT) which is now present in the television set of every home and on the desk of every office worker.

Another example originates in a problem which is still with us to-day, to count events. In the early decades of this century physicists were studying the decay of radioactive elements. Although the detectors were rather crude, the rate at which they could register events did exceed the capability of the electro-mechanical counters used for this purpose. However, by connecting in a clever way two vacuum tubes it was possible to build an electronic counting circuit without moving parts called flip-flop, capable of
accepting a much higher rate of events than its electro-mechanical counterpart. Flip-flops are now made with semi-conductors drawn at a submillimetric size on the surface of silicon chips rather than with bulky, fragile and heat dissipating vacuum valves; they constitute the essential building blocks of digital computers (registers in the arithmetic unit and basic constituent of the direct access memory circuits). To-day flip-flops are at work in every pocket calculator, in every shop cash-register and in the other thousands of computer applications which drive the present information revolution.

To-day particle physics requires complicated and large scale devices. To study the ultimate constituents of matter one still uses the basic principles of the microscope. One needs a source of light to illuminate the object one wants to observe and a suitable detector to collect the rays scattered by the object. As one goes down in scale, the laws of optics require the use of shorter wave lengths which in quantum mechanics are associated with particles accelerated to increasingly higher energy, hence the large size of modern front line research particle accelerators which now extend over tens of kilometers. The detection of the events resulting from high energy particle collision requires large and complex detectors since it is necessary to be able to account for the total energy involved and, therefore, track all the particles produced in each event. Finally extensive computer power is needed to reconstruct the interactions and sort among billions of events, those of interest which contain new information.

The construction of these large devices involves the utilisation of a variety of techniques such as heavy and light mechanical and electrical engineering, vacuum, surface and material sciences, electronics and computer science. Progress in the experimental facilities requires a constant demand for improved technical performance.

Higher magnetic fields for the accelerator magnets and the detector spectrometers, and more powerful microwave generators to produce higher accelerating fields have been developed. Better vacuum was achieved as accelerators have evolved into colliders or coupled to storage and stretcher rings in which particles must be kept for hours or even days without significant losses. Efficient power conversion devices, magnets and accelerating structures which minimize the electricity consumption and, therefore, the operating cost have been designed. This latter constraint together with the demand of high fields, has prompted the present development of superconductivity and the associate cryogenics engineering which is maybe one outcome of particle physics with the best medium term prospect for widespread spin-off. The electronics and control systems of large particle accelerators and the data acquisition systems of experiments have also led to new technical concepts. Detector devices such as scintillators and, more recently, the multiwire proportional chambers find application in medicine while particle accelerators themselves are finding wider and wider medical and industrial applications; they are also beginning to be used as new radiation sources such as synchrotron light or free electron lasers which have unmatched properties and will certainly lead to numerous applications.

These technologies will be briefly reviewed in the next chapters, with particular attention to their utilisation in other fields\textsuperscript{1}.
2. SUPERCONDUCTIVITY

A major limitation of classical electric and electromagnetic devices is due to the finite electrical resistance of the conductors leading to ohmic losses. In fact, the size and the ultimate performance are set by the practical limits of providing for the dissipation of the heat generated by these losses. The property exhibited by some metals and alloys to lose their electrical resistance when cooled to temperatures of a few degrees Kelvin, i.e. the phenomenon of superconductivity, was, since its discovery in 1911, considered of great potential interest. Unfortunately, in most materials this property is destroyed by even weak magnetic fields. It was only in the late 1950's that alloys such as NbTi which preserve their superconducting property in the presence of strong magnetic fields were discovered, opening the way for application of what was until then a laboratory curiosity.

The first large scale use occurred a few years later for spectrometer magnets built to analyze high energy particle events, in particular the large bubble chambers. The fields were in the 2 to 3 Tesla region and although not yet significantly higher than what could be achieved with conventional copper coils and iron yoke already allowed significant volume and weight reductions and considerable electric power savings. These early applications were for static magnetic fields; even slow magnetic field variations led to unacceptable heat dissipation in the conductors. Towards the end of the 1960's a development breakthrough was achieved at the Rutherford Laboratory which resulted in the production of intrinsically stable conductors consisting of twisted thin strands of superconducting wires embedded in a copper matrix suitable for ramped synchrotron and collider magnets.

A first application in an operating accelerator was the construction and operation of superconducting quadrupoles to increase the luminosity of the CERN Intersecting Storage Rings. This was followed in 1984 on a much larger scale at Fermilab by the commissioning of the Tevatron, a ring of more than 1000 pulsed bending and focusing magnets installed in the 6 km circumference tunnel of the existing accelerator which operates in the 4 to 5 Tesla range. In Europe similar developments are taking place where a ring of magnets of about the same size with somewhat higher expected performance (5 to 6 Tesla), is now under construction for the HERA project at DESY, Hamburg. At CERN one is studying a large hadron collider to be located in the 27 km long LEP tunnel now being bored. As the size of the tunnel is fixed it is essential to aim at a magnetic field as high as possible; 8 to 10 Tesla now appear realistic and a development of suitable conductors and magnets is now being launched in collaboration with European research institutes and industry.

Another major component of high energy accelerators, where superconductivity can bring both increased performance and large energy savings during operation is in the radio-frequency structures needed to accelerate the beam. The classical copper cavities are limited by the level of the ohmic losses in their walls. Positive results have been achieved at CERN in the development of RF cavities for the second phase of LEP.
achieved at CERN in the development of RF cavities for the second phase of LEP. Superconducting cavities will allow to upgrade the energy from 50 to 90 GeV per beam. Impressive progress has in particular been made in the accelerating field where values of 10 MV/m have been achieved. In high energy circular electron machines a large amount of synchrotron radiation is emitted and must be compensated by the RF system, whereas the problem in linear machines is to increase the duty cycle which is very low (typically in the $10^{-4}$ to $10^{-3}$ region) because of power limitations. The use of superconducting cavities allows the design of a machine capable of delivering a continuous beam and opens up a new range of nuclear physics research possibilities. A longer range application is the use of superconducting cavities in large linear colliders.

Superconductivity has, however, many potential applications outside the field of fundamental research. The practical implementation of a fusion reactor, either based on magnetic or inertial confinement, will probably rely on superconductivity. In the case of magnetic confinement, a net energy gain can only be achieved if the confining magnetic field does not require excessive power. Furthermore, the high magnetic fields permitted by superconductivity can compensate for scale in fusion and allow the design of more compact machines. The next generation of major tokamaks between machines such as JET and the first commercial fusion reactors is designed with superconducting magnets capable of reaching 10 to 12 T.

Research on inertial confinement fusion is progressing on several paths as to the way to achieve the implosion of the fuel pellet. Particle beam driven systems are based on ideas resulting directly from particle physics research and the most promising suitable laser system, the free electron laser (see section 10) derives also from the particle accelerator technology. Although present research devices are classical it is likely that for reasons of conversion efficiency, the use of superconductivity technology will be essential in commercial units.

Besides power generation by nuclear fusion, superconductivity is also being studied for other electrical engineering applications.

The rating of electric power generators has grown from 50 MVA in the early 50's to 1500 MVA in modern nuclear power stations. The generator weight per unit output was at the same time reduced from 2 kg/kVA to less than 0.5 kg/kVA by improving the cooling which allowed higher current densities. This was, however, also connected with a rise in ohmic losses and a reduction in efficiency which has prompted numerous developments based on superconductivity throughout the world. Following a series of small models (18 projects of less than 10 MVA have been recorded), several experimental generators rating between 10 and 50 MVA have been built in the early 80's to test specific design problems and assess the operational performance. An 850 MVA commercial size superconducting generator adapted to the rating of large modern coal fired power plants is now being developed in Germany.

Transmission of electric power is another possible application of superconductivity. The prospect of replacing the several hundred meters wide electrical highways at the
entrance of large cities by an underground superconducting cable is an attractive proposition. Successful tests of a two conductor 60 Hz, 115 m long flexible cable capable of transporting 1000 MVA in 3 phase service have been carried out at Brookhaven National Laboratory and open the way for the installation of longer transmission lines\textsuperscript{14}

Another possibly very far reaching application of superconductivity in power engineering is the large scale storage of electricity. Large coal-fired and nuclear power plants are designed to operate at full or nearly full capacity. Their expected life-time is decreased significantly if they are forced to cycle by large fractions of their capacity. On the other hand electricity demand is submitted to large seasonal, weekly and daily cyclic variations. A variety of technologies ranging from gas turbines to pumped hydro-electricity are currently used to meet these variations, but have drawbacks such as the uncertainty of fuel cost variations or the availability of suitable sites which would make new techniques such as SMES (Superconducting Magnetic Energy Storage) attractive\textsuperscript{15}. One of its main advantages is that energy is stored in its electrical form and requires no conversion from or into thermal or kinetic energy. Reference systems for 5 GWH have been designed in the US and Japan\textsuperscript{16}. It would have a 150 to 200 m coil radius depending on the aspect ratio. The feasibility of the concept has been successfully tested in a 30 MJ system installed in 1982 to stabilize the electric power transmission between the Pacific Northwest and Southern California\textsuperscript{17}.

High speed ground transportation could also become a large scale application of superconductivity which relies on the mechanism of magnetic levitation\textsuperscript{18}. A 10 ton Japanese test vehicle using an electrodynamic scheme whereby levitation is achieved by the reaction of eddy currents created by an electro-magnet moving above a conducting rail has reached a speed exceeding 500 km/h\textsuperscript{19}. Superconducting coils fulfill the three functions of suspension, guiding and propelling the vehicle. Similar developments are also taking place in Germany.

Another industrial application of superconductivity is magnetic separation for mineral and scrap metal processing. This utilisation requires high magnetic forces in extended volumes to achieve high throughputs when the separation of weakly magnetic particles is desired. The low power requirements of superconducting systems offer promising prospects\textsuperscript{20}.

It is important to note that in all these industrial applications of superconductivity, a.c. operation is an essential requirement and one must remember that these suitable conductors were first developed in view of constructing synchrotron magnets.

Eddy currents induced by superconducting magnets could slow the convection currents during the crystallisation process of silicon for semiconductor production. This would lead to more homogeneous crystals and therefore allow to manufacture larger single chip devices.

Another possible application would be ultra-fast computers based on the faster switching properties of Josephson diodes.
Superconductivity is also now finding application in medicine as superconducting magnets are getting into widespread use for NMR scanners which offer the great advantage of being non-invasive compared with classical X-ray diagnosis techniques.

3. **CRYOGENICS**

Cryogenics, the technology of low temperature, is closely associated with superconductivity. All known superconductors operate in the region of a few degree K and cooling is most conveniently achieved by using liquid helium. High Energy Physics had been for a long time familiar with the use of low temperature on a large scale since one of the most widely used detector types of the 1960's and early 70's was the liquid hydrogen bubble chamber which was using and leading to further development in cryogenic technology. The know-how was readily available for superconductivity applications. The cryogenic system of the Fermilab Tevatron, consisting of a 5000 l/h central helium liquefier coupled via liquid transfer lines to 24 satellite refrigerators feeding strings of magnets is an impressive example of the state of the art.\(^{21}\). Of the technical evolution that has led to this and to similar realizations and that can be extrapolated into the future, here are just two examples: turbines for the generation of very low temperatures by close-to-isentropic expansion of helium gas have been developed to technical maturity, largely in response to specific needs of particle physics laboratories, in the 1960's and 1970's; this development is likely to continue and to extend to turbines ('wet turbines'). Even the simple, but not very efficient classical Joule-Thomson expansion process has been improved by the introduction of ejectors to reach lower temperatures at minimum capital investment.

Most present superconducting magnets use NbTi wire and operate at temperatures close to 4.2 K, the normal boiling point of helium. At this temperature, the field achievable with NbTi is limited to about 6.5 Tesla. Higher fields would require either better superconductors or lower cooling temperatures.

Unfortunately, all known superconductors with the desired magnetic properties, e.g. the intermetallic compound Nb₃Sn, show very unpleasant mechanical features such as extreme brittleness and have resisted all attempts of producing cables suitable for economic manufacturing of high-quality coils until now; nevertheless, impressive development programmes to overcome these difficulties are under way in various industries.

The alternative approach, cooling below the normal boiling point of helium, would substantially improve the performance of classical NbTi (about 10 T could be reached at 1.8 K), but would require to overcome two main barriers, high energy cost for cooling (even in an ideal process, energy requirements are, according to the second law of thermodynamics, inversely proportional to the cooling temperature) and operational difficulties with large helium systems at subatmospheric pressure, where poor heat exchange and high flow resistance in the gas phase result in bulky, expensive and otherwise problematic heat exchanger and transfer line designs. Here development work is focused on improved cryostat design and on compressors operating at temperatures below 10 K with reasonable efficiency, i.e. with an entropy production not substantially higher than that of traditional 'warm'
compressors: such machines would eliminate a great deal of the problems of low pressure in the cryogenic systems. Other work aims at applying the cooling principle of adiabatic demagnetization of paramagnetic salts, traditionally used for cooling at laboratory scale in the mK temperature range, to the much higher cooling powers [at considerably higher cooling temperatures] required for typical superconducting systems.

It must be noted that the temperature range around and below 2 K would offer, once the access problems are reduced to an acceptable level, some very attractive features: liquid helium undergoes at a temperature of 2.17 K a transition to the superfluid state characterized by an enormous increase of thermal conductivity and reduction of viscosity, properties of great interest for many practical applications.

Cryogenics is applied in other fields, in particular in vacuum and space science and for sensitive instrumentation such as low noise amplifiers or the detector of the infra-red astronomical satellite.

Nuclear magnetic imaging systems using superconducting magnets find rapidly increasing applications in diagnostic medicine; they constitute an enormous challenge to the design of cryostats of the highest efficiency for use in hospital environments.

4. VACUUM AND SURFACE SCIENCE

The acceleration of particles requires the production of a good vacuum to avoid the scattering of the beam by the residual gas. Pressures in the region of $10^{-6}$ to $10^{-7}$ Torr are generally sufficient for synchrotrons in which the accelerating process lasts only a few seconds. Storage rings and colliders which must store beams for periods extending over several days have more critical demands and must operate in the $10^{-10}$ to $10^{-11}$ Torr range. Even lower pressures are desirable in the vicinity of the detectors to reduce the background due to collisions with the residual gas. The construction and operation with a continuous performance improvement of the CERN Intersecting Storage Rings (ISR) has in particular brought much progress in this field.

Techniques for cleaning and preparing surfaces such as the glow discharge to reduce ion and photon induced desorption were developed, extensive pumping systems consisting of hundreds of units (300 sputter ion pumps and 700 Titanium sublimation pumps were installed on the ISR) were operated reliably without interruption for periods exceeding a thousand hours allowing to reach average pressures of $3 \cdot 10^{-12}$ Torr. The construction of the Large Electron Positron collider (LEP) is also stimulating progress in vacuum technology. It has for example led to the development of a linear non-evaporable getter (NEG) pump constituted of a Zr-Al alloy bonded in powder form on a constant ribbon. Another development has been the all aluminium vacuum chamber which, compared with stainless steel, has better thermal conductivity, lower residual radioactivity and can easily be extruded to obtain the required complicated cross section.

Other vacuum system components have been developed following the requirement of accelerator systems, in particular mechanical motion under vacuum. As pressure falls,
lubrication is prohibited and frictional effects increase dramatically. Ingenious solutions had to be found to perform motions required for fast closing valves, beam diagnostic devices or shutters and movable sensing electrodes and deflectors. Vacuum seals have also undergone considerable improvements. Elastomers cannot sustain high radiation environment and metal joints have now been generally introduced.\textsuperscript{25}

All this progress in vacuum technology is finding direct applications outside the field of particle physics research in particular in space science, fusion test facilities, heat insulation of cryogenic systems and industrial applications such as ion implantation technology for semi-conductor manufacturing.

5. MECHANICAL ENGINEERING

The construction of the components of particle detectors and accelerators involves many facets of mechanical engineering and the requirements made by the physicists have advanced the state of the art in several areas. Here one can only give a few examples to illustrate the variety.

In colliders the particle detectors must be placed as close as possible to the beam which circulates in a vacuum tube. The beam must not interfere with the vacuum tube and the metallic vacuum pipe should ideally not intercept the products of the collision event. The solution was the design of thin shells which interact minimally with the collision products but nevertheless preserve the vacuum integrity and resist external atmospheric pressure.

Experiments require many unconventional materials such as lithium and beryllium because of their low atomic weight, niobium for its superconducting properties, titanium and composite material for both their lightness and mechanical strength properties. Ceramics and epoxy resins which are both good electrical insulators and are radiation resistant, ferrites for their high frequency behaviour, plexiglass for its light-guiding properties and many others. More common materials such as copper, aluminium or stainless steel must be shaped, machined and welded into unconventional configurations while preserving vacuum tightness at cryogenic temperatures. Furthermore, high cleanliness is essential to avoid degassing and maintain the capacity to withstand high voltages and high electric fields. For this purpose techniques of chemical machining of exotic materials (photoengraving), chemical and electrochemical polishing, thick deposits onto complex shapes and electroforming have been developed.

For instance, technologies like electron beam welding have been used successfully to manufacture superconducting niobium RF accelerating cavities or, with local vacuum, for welding the aluminium plates which constitute the windings of one of the new large detectors which will operate with LEP\textsuperscript{27a}). Laser cutting and welding are now finding a growing field of application.
The thin film technology is also widely used to create a conducting or resisting film made out of metals like Ti, Ta, Al, Au, Pd, Ge, Nb on a variety of substrates resistant to high temperature and radiation ('kapton', quarz, alumina), or to deposit optical coatings on large surface mirrors (e.g. Al + MgF to improve the ultra-violet reflectivity in Cerenkov counters).

Remote handling has been essentially developed for the nuclear industry. However, additional features such as pressure feeling feedback or spools suitable for fiber optics cable in view of long range action have been introduced to cope with the special environment of particle accelerators. Some of these developments are of interest for the maintenance of nuclear reactors \[ 27b \].

When considering mechanical engineering it does not appear at first that particle physics as such has been the source of new advanced technologies. But it does contribute to their extension in sometimes unexpected fields such as the use in shipyards of a vehicle designed at the request of CERN for moving, without deformation, heavy magnets which have been assembled and measured carefully with high precision in the laboratory. The application of this technique in ship-building allows to cut and machine ship elements in the workshop rather than in situ on the yard itself with an appreciable gain both in quality and cost \[ 28 \].

6. RADIO-FREQUENCY AND MICROWAVE

The acceleration of particles is achieved by high frequency fields excited in suitable structures. One uses mostly tuned resonant cavities which have a high quality factor and allow to reach a high accelerating field with reasonable energy dissipation. A similar technology has also been used in experimental areas to separate, by transverse high frequency fields, particles of different momenta. Depending of the type of machine a wide range of frequencies is used from the few Megahertz into the several Gigahertz region. While fixed frequency systems are suitable for the acceleration of electrons which are already fully relativistic in the MeV energy range, variable frequency systems are necessary for proton and ion acceleration well into the multi-GeV range.

In circular machines the beam travels in a ring and receives repeatedly, at each turn, an energy gain from the RF system. The requirements can be satisfied with industrial equipment developed for radio and television broadcasting. This is, however, not the case for linear accelerators in which the beam passes through only once. In particular the developments for higher power and duty cycle at the Stanford Linear Accelerator Center for its 2 mile long, initially 20 GeV electron linac, brought dramatic improvements in the state of the art of klystron in the S band (GigaHertz region). Radar applications, in which this technology, arose, show in general little concern for efficiency, whilst it is a decisive factor for the operation of a research installation and S-band klystrons with peak power outputs of 30 to 50 MW are now available with efficiencies up to 50\% \[ 29 \]. This technology is now also developed in Europe for the injector linac of LEP in particular. A
fifteen cavity tube which delivers 37 MW peak with an RF pulse length of 5 μsec and average power of 20 kW at 3 GHz has been produced. This development is extended to other applications such as free electron lasers with longer pulse lengths\(^30\).

In a high energy electron ring such as LEP the performance limit is set, among other parameters, by the beam emitted synchrotron radiation. While the development of superconductive RF cavities will reduce the cavity losses, the synchrotron radiation must still be supplied to the beam and its amount increases as the 4th power of beam energy. This has stimulated the development of CW high power RF generators. A 1 MW klystron designed to operate at 353 MHz has been successfully developed by industry with an efficiency approaching 70%\(^30\).

High power klystrons are also of interest to the fusion community which requires techniques for plasma heating. Accelerator technology is also used for the same purpose to produce neutralized particle beams.

Proton linacs and proton accelerators operate with RF systems in a lower frequency range (10 to 200 MHz) where gridded tubes such as triodes and tetrodes are used to provide RF power. Accelerator developments have also stimulated improvements such as the pyrolytic graphite grid which allows tubes to run at higher temperatures and achieve higher power outputs\(^31\).

While accelerating systems work normally at a single frequency or in a narrow band, the new technique of stochastic cooling has generated the requirement of broad band amplification and power output in the Gigaherz frequency range. Without entering into the theory, it is sufficient to say that the increase of the number of particles to be cooled requires a corresponding increase in the bandwidth of the correction signals necessary to achieve the cooling. This has led to the development of field effect transistor amplifier modules capable of delivering several kilowatts in a 1 to 3 GHz frequency band\(^32\).

7. **ELECTRICAL ENGINEERING AND POWER ELECTRONICS**

The powering of large particle accelerators magnets represents non-trivial problems in the heavy electrical engineering field. The operation of a synchrotron requires to increase the guiding magnetic field in step with the increasing energy of the particles. Once the top energy is reached, the magnetic field must be kept constant with a stability of \(10^{-4}\). The power supplies must have the capability to adjust the value of the current according to the energy desired for a given experiment and achieve from cycle to cycle a reproducibility of \(10^{-4}\) to \(10^{-5}\). The pulsing of large synchrotron magnets requires power swings in the 100 MW range. In the 1960's this was achieved for the CERN PS and the Brookhaven AGS by specially designed rotating motor generator sets equipped with flywheels which stored the energy during the de-energizing fraction of the cycle to avoid load fluctuations on the mains\(^33\). It is worthwhile noting that this development by a European firm was also adopted by an American laboratory, a fact which was not very common at that time.
For the powering of the next generation of accelerators such as the Fermilab and the CERN SPS machines the power swings would have been excessive for a rotating machine of acceptable size and it was decided to power directly the machine from the electricity grid. This solution did, however, require the development of an original scheme of reactive power compensation to maintain the voltage fluctuations of the main grid at an acceptable level\textsuperscript{34}. 

Another stringent specification for some of the particle physics power converters is the condition of low voltage ripple associated with stability and reproducibility in the $10^{-4}$ range for which 24-phase supplies together with active filters were designed\textsuperscript{35}. 

With the increasing power requirements of new accelerators (in its first phase, the new LEP collider now under construction will need 70 MW), power conversion efficiency has become an additional but essential specification. The LEP main, auxiliary and correcting magnets will need about 700 power supplies ranging from 1 kW to 4 MW. They have to operate in two different modes: acceleration during which all the converters must be ramped in accurate synchronism and achieve a following error of $10^{-4}$; steady state during which physics data taking occurs and one must maintain a precision of $10^{-4}$. Precision being defined here as the sum of "long term", "short term", stability and residual ripple with the ripple component kept to values approaching $10^{-6}$\textsuperscript{36}. 

While high power units are based on conventional thyristor line-commutated power supply modules, it has been found possible to use, for the numerous intermediate and low power units (from 40 kW downwards) the more efficient switched-mode scheme\textsuperscript{37}. Prototype modular units with switching currents of 100 A at 10 kHz have been successfully constructed, advancing the state of the art into a new power range. 

Particle accelerators require not only accurate and stable DC or ramped power supplies, but also some of their elements need intense and fast pulses which must be triggered with high precision and very low jitter to ensure timing for beam transfer with nanosecond accuracy. This has led to the development of a variety of pulse generators\textsuperscript{38,39} and also to substantial progress in industrial thyratron switches\textsuperscript{39}. Research for better high power and high speed switches has also stimulated the study of new plasma processes such as the pseudo spark which may have promising applications in the field of high power pulsed devices and also as a new beam source\textsuperscript{40}. 

Direct current transformers have been developed to measure the intensity of accelerator beams and are now produced by industry for high accuracy current monitoring. 

8. ELECTRONICS

Particle physicists use a large variety of physical phenomena to detect the particles they want to study. For many years one of the most useful and versatile devices was the
bubble chamber in which the data were registered on photographic films. To-day, however, most experiments are based on techniques which yield electronic signals which lend themselves much better to digitization prior to computer processing. It is impossible to give here even a broad overview of the vast field of electronics associated with particle physics and one can only attempt to give a few examples.

The basic information on the physics events is contained in the amplitude and the timing of the signals. The key circuits are analog to digital converters (ADC) and time-to-digital converters (TDC). Classically the amplitude and time arrival of the signal were converted to a charge on a capacitor then digitized by measuring discharge time. The digitizing may take several hundreds of microseconds depending on the system clock frequency and on the required resolution. The duration of this conversion process was completely inadequate in view of the data rate produced by the new generation of electronic detector assemblies built around colliders. The answer was the development of the flash analog-to-digital converter (FADC) which consists of a parallel array of differential comparators connected to a resistor string reference network and followed by a set of logic gates to ensure the encoding. Thanks to the progress of very large scale circuit integration (VLSI) it is possible to put several hundreds of comparators on a single chip and build arrays of FADC's at a reasonable price.

The evolution of the experimental analysis technique with in particular on-line computer data treatment, together with the fact that high energy physics experiments are now all conducted by international teams coming from many different institutes, created the need of having a common standard for the data acquisition and its interfacing to computers. Such a scheme named CAMAC was developed in Europe in the late 1960's. It consists essentially of a standard dataway connecting acquisition electronic units to a computer with appropriate control signals. To extend its scope of utilization, the initial parallel dataway which permitted only short distances between the electronic units and the interface crates was completed by a serial standard giving much more freedom. Another attractive feature is the modularity with standard building blocks adaptable to a variety of applications without additional development. CAMAC has enjoyed a wide success much beyond the world of particle physics and is now widely used in other fields of research such as space and fusion for data acquisition systems, but also for computer controlled systems in many industries, such as blast furnaces and rolling steel mills, aluminium ingot casting, polymer production, food processing, flight simulators, aircraft engine testing, power plant fire protection and many others. Modules designed for particle physics have in these cases been readily purchased by industry.

The increasing rate and quantity of data of particle physics experiments created the need in the late 1970's of a new data acquisition standard which would allow greater speed (ten times the CAMAC speed which has a basic clock rate of 1 MHz in the parallel mode and is much slower in the serial mode), segmentable and parallel processing and a bus architecture allowing a wider variety of uses than permitted by CAMAC. Such a standard has been defined and named FASTBUS. It has spread rapidly in the particle physics community and is the agreed system for all the new large physics experiments. Although not yet as widely used as CAMAC it is already attracting interest in other fields (it is, for
instance, being used to study the generation and transmission of electric nervous signals in neurology research\(^{(7)}\).

Modern experiments are also characterized by a very large number of signal-processing channels \((10^5 - 10^6)\) analog-digital channels. It required substantial development to reduce the size, power consumption and price of this instrumentation.

9. COMPUTERS AND COMMUNICATIONS

In a large particle physics research centre like CERN there are hundreds of computers ranging from big main frame machines such as the IBM 3090 or the CDC Cyber 875 (to be phased out in October 1986 and be replaced in 1987 by a Cray-XMP-48) of the central computing centre through large dedicated machines such as the DEC VAX 8800, to a great number of smaller machines directly connected to experiments and performing on-line data-taking tasks. The controls of the large particle accelerators also require several tens of medium-size computers, without taking into account the growing quantity of microprocessors which are numbered by the thousands and directly incorporated in the manifold measuring and monitoring instrumentation.

Again it is difficult even to list the numerous applications of a more general interest which have come out of this field and one can only give some examples.

As a substantial part of the analysis of data produced in high energy physics experiments is done not at CERN but by computers in the home institutes all over Europe, the need arose to design and build a network to ensure data transmission and communications between these computers and share the available data treatment power. Although this problem was not peculiar to particle physics, one of the constraints was to adapt this network to the large variety of equipment from different suppliers which had to be connected together\(^{(8)}\). It has been extended in some cases via satellite links to computers in Member State institutes (the COST funded STELLA experiment). CERN is recognized as a major site in the research and academic wide-area network community.

Distributed computing has also been developed in the real time environment of the controls of particle accelerators. The first of these distributed systems was developed for the CERN SPS\(^{(9)}\), extended to other CERN accelerators and other advanced technological fields, such as test fusion facilities\(^{(50)}\).

This has been accompanied by numerous software developments; an example is the Remote Procedure Calls whereby a procedure with its parameters, instead of being executed in the initiating computer, is transmitted and executed in a different machine\(^{(51)}\). This application which originated in the problem of the interaction between an operator working on one of the general purpose consoles of a control room with equipment controlled by a separate specialized computer, which could be located several kilometers away, is relevant for a wide variety of distributed computer problems like distributed data-bases or distributed mail systems. It has attracted the interest of the European Information
Technology industry and CERN is participating in a project within the framework of ESPRIT: a development concerning 'name servers' or in other words a distributed directory.52)

On the hardware side, attention has been devoted to the man-machine interface in the complex accelerator control rooms. Control rooms were traditionally filled with rows of racks each directly wired to the process and allowing to monitor and control a machine subsystem. This arrangement has been replaced by general purpose computer driven operator consoles from which any part of the process can be accessed. One of the associated developments was the so-called touch panel, a special purpose CRT screen on which the equivalent of a classical push button control panel is displayed in the form of identified labelled squares. It can be actuated by touching the appropriate area of the screen. The screen display is changed with the process or subprocess which the operator wants to control so that the whole system, whatever its size, can be controlled from a single console.49) Some of these concepts are being adapted elsewhere and have in particular attracted the interest of the designers of electrical power plants.

10. NEW RADIATION SOURCES

Two fundamentally new mechanisms for generating electromagnetic radiation of both higher quality and higher intensity than previously available, have recently emerged from particle physics research: synchrotron radiation and free electron lasers (FEL).

Synchrotron radiation is the electromagnetic radiation emitted by relativistic electrons travelling on curved paths.53) It was first observed in electron synchrotrons, hence its name, and then considered a parasitic effect absorbing a fraction of the power required for acceleration and ultimately limiting the energy of the machine. However, its unique properties soon made it a new and powerful research tool which also opens up promising industrial applications. It is now extensively used in a symbiotic manner with the high energy physics programme, but there are also more and more dedicated facilities. Over twenty are already in operation54) and another twenty are planned or under construction55).

The most important characteristics of synchrotron radiation are its tunability and the high and extremely stable intensity over a broad bandwidth. This frees researchers from working only at the discrete lines available from conventional ultra-violet and X-ray sources. Synchrotron radiation makes available more than $10^5$ higher fluxes than the most powerful conventional X-ray sources and will for instance allow to elucidate problems such as crystal growth or mechanical failure processes on a millisecond time scale and also investigate biological systems.

Many X-ray detectors used in these studies are based on techniques originally developed for particle physics (see sect. 12).
Another property is the extreme collimation (the radiation is emitted in a cone with an opening angle of less than 1 mrad for storage rings with energy of 1 GeV). This permits to produce highly monochromatic beams and, therefore, the use of soft X-rays for the fabrication of lithography of microstructures such as memory devices, Josephson junctions and integrated circuits. The source can be imaged on very small samples to study electronic structure and surface processes such as oxidation, catalysis and corrosion.

Other characteristics such as the time structure and the high polarisation are features which increase the versatility of applications. One is, for instance, considering the possibility of pumping X-ray lasers, or others which require high spatial and temporal densities, X-ray holography and the general field of radiation chemistry and technology which would permit to modify the surface and bulk properties of materials.

The Free Electron Laser (FEL), though proposed in 1971, is not yet so developed. Its operation is based on a high quality relativistic beam of electrons passing through a periodic magnetic field to amplify a copropagating optical wave. In an oscillator configuration, the light is stored between the mirrors of an optical resonator. In an amplifier configuration the optical wave and the electron beam pass through a transversely undulating magnetic field to achieve high gain. In either case, the electrons must spatially overlap the optical wave to achieve good coupling. The peak electron beam current may reach several hundreds of amperes with electron energy ranging from a few MeV to several GeV. This principle allows the construction of very powerful lasers (Gigawatt range) and the close coupling between particle beam and electromagnetic wave should permit a high efficiency. Energy extraction of 5% of the electron beam energy has already been demonstrated, but much higher values appear feasible.

An essential characteristic of this laser is that the frequency is not narrowly determined by the energy levels of the lasing material but it can be continuously tuned by changing the electron beam energy. Low energy beams (5 MeV) are being used to reach wavelengths longer than atomic lasers (500 μm), while GeV beams permit to reach the X-ray range (500 Å).

So far the Free Electron Laser is still in the development stage of the physics laboratory but the prospects of an efficient, powerful, reliable and tunable source of coherent radiation are certainly going to open up many applications, inertial confinement fusion being the first among them.

11. **INDUSTRIAL ACCELERATORS**

The present industrial applications of particle accelerators fall under two broad categories: ion implantation and radiation processing which have both undergone rapid development in the past few years.
According to a 1984 estimate in the Western world there were 1500 ion implantation accelerators increasing at an annual rate of 35%. Ion implantation consists of introducing ions of a specific type in a depth of a fraction of a micron to change the material properties of a base substance. The parameters which can be modified in this way are among others, electric conductivity, hardness, wear behaviour, friction coefficient, resistance to corrosion, fatigue behaviour, adhesive properties and catalytic behaviour.

By far the largest application today is the manufacture of semiconductor products where ion implantation is progressively replacing the ion diffusion process. Ion implantation allows to fabricate very compact devices. The use was at first limited to low energy beams of a few hundred MeV produced by multi-stage voltage multiplier machines. With the advent of more powerful electrostatic belt generators operating like the tandem ion accelerator with charge exchange, energies of 3 MeV can be reached with triple charged ions. It is then possible to achieve penetration depths exceeding one micron and modify the bulk properties of a device rather than only its surface behaviour.

Modification of mechanical properties by ion implantation has not yet reached a large commercial market but there are promising prospects such as in the medical field where the life-time of artificial joints could be drastically improved.

Improvements in the power level and reliability of electron linear accelerators stimulated by their development for particle physics have now made them cost-competitive with alternative sources of ionizing energy such as cobalt-60 for applications such as radiation processing for which accelerators are more flexible and easier to use, as they can easily be turned off which is not the case of radio-isotopes. Three hundred operational industrial electron beam accelerators were reported at the last International Conference devoted to that subject. They are in the 5 to 10 MeV range with power up to 200 kW.

The main applications are:

- Sewage and sludge treatment where irradiation eliminates pathogenic germs and allows the sludges to be used as fertilizers. Its use as ruminant animal feed has been demonstrated and the process is being found more effective than chlorination for destroying eggs and larvae of parasites and viruses.

- Food preservation where radiation processing will allow to eliminate the use of chemicals for preserving products such as meat, poultry, fish, animal feed, fruit and vegetables. The availability of this new process is particularly timely as previously used chemicals are being prohibited for health reasons.

- Sterilisation of disposable medical products such as syringes, operating room gowns, gloves, bandages. Here again radiation processing is being substituted for chemicals, which are now considered noxious.

- Disinfection of biological toxic waste from hospitals and other health care facilities.
- Treatment of flue gas to remove sulphur and nitrogen oxides. The electron beam is used to excite these molecules so as to ease the conversion of the oxides into acids which are reacted into more easily removable compounds.

- Material processing. Electron beams will initiate polymerisation and improve the adhesion of coatings; they improve the physical and thermal properties of the polyethylene insulation of electrical wires and cables. Ion bombardment modifies in a 'useful way' the surface properties of some metals.

- Mechanical engineering development, in particular wear studies.

Other even more interesting applications such as the degradation into sugar or liquid fuels of the cellulosic waste from the forest industry and detoxification of chemicals like PCB for which there are no substitutes, are not yet commercialised, but their feasibility has been demonstrated in the laboratory. The disposal of radioactive waste has also been contemplated but no practical scheme has been reported so far.

12. MEDICAL TECHNOLOGY

Particle physics is at the origin of a variety of new medical technologies for diagnostics and therapy.

We have mentioned in the section about superconductivity the rapid development of Nuclear Magnetic Resonance (NMR) imaging (300 new installations/year in the world) for which the availability of reliable and powerful magnets with an already proven technology has been a decisive factor.

High energy physicists have developed a large variety of high resolution particle detectors to observe and analyse particle behaviour. One of them, the Multiwire Proportional Chamber (MWPC) has found several applications in nuclear medicine for proton radiography and imaging of X-rays, gamma-rays and neutrons. A particular further successful development is the Positron Camera. It consists of two high density multiwire chambers optimized to detect by coincidence the pair of gamma rays emitted by the annihilation of a positron in matter. This gives both positional and directional information which allows with tomographic reconstruction methods to obtain three-dimensional images. This device initially developed in the CERN environment is now commercialized. It has given rise to Positron Emission Tomography (PET). Positron emitting radioisotopes when injected in living organisms can give unique biochemical and physiological information. One can then follow changes in the distribution of tagged atoms, observe anomalies of metabolism (changes in blood flow, oxygen utilisation, glucose metabolism) or detect tumours.

Positron emitting radioisotopes produced by accelerators 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 isotopes of interest are carbon 11, nitrogen 13, oxygen 15 and fluorine 18. They are short-lived and can be injected into 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 utilised on the same site by dedicated facilities.\textsuperscript{65}

Newer technologies such as solid state silicon microstrip detectors offer higher resolution and also originate from high energy physics research.\textsuperscript{66} They may, in the next few years, offer even better diagnostics means.

Particle accelerators find now an increasing field of application in radiotherapy. The scope of this application can best be appreciated when one realizes that approximately 25\% of the population of developed countries will have to cope with some form of cancer in their life-time and about one half of the cancer patients receive radiation treatment. The two most common methods of administering radiation therapy are radioactive gamma sources (cobalt-60) and accelerators. Radiation produced by accelerators is more versatile and can provide deeper penetration when necessary. In 1982 there were about 700 electron linacs (500 below 10 MeV and 200 above 10 MeV constituting over 50\% of the U.S. radiotherapy installations).\textsuperscript{67}

Because of their high penetration and biological effectiveness, neutrons are deemed by their proponents to be more advantageous than conventional photon therapy in 20\% of the cases. Neutrons are generated by the reaction of 250 keV deuterons on a tritium target. Fluxes of $4 \times 10^{12}$ neutrons/second are necessary and target life-times have been one of the major problems for achieving operational installations. It is also envisaged to use cyclotron produced neutrons (40 MeV protons on a beryllium target).\textsuperscript{68}

Negative pions, protons and heavier ions offer the possibility of improving the therapeutic ratio between malignant tumours and healthy tissues.\textsuperscript{69} Heavy charged particles can achieve a highly localized effect. The so-called Bragg peak (region of maximum energy deposition) is only a few millimetres wide near the end of the range, which allows to deliver a high dose with less damage to the overlying tissues. The required penetration depths make it necessary to use machines capable of producing particles in the several hundreds of MeV range. Present installations have still an experimental character and are located near accelerators built for other purpose (SIN, LAMPF, FNAL, TRIUMF, Dubna,...) but dedicated therapeutic facilities are under design.\textsuperscript{70}

In contrast with radiotherapy proper which involves radiation dose delivery to a large tissue volume by a large number of exposures delivered over several weeks, charged particle radiosurgery is a treatment of a well defined target, for instance an intracranial lesion, with a narrow particle beam delivered in one or a few fractions. Results comparing the effects of various ions in the 100 to 500 MeV range have been reported.\textsuperscript{71}
13. OUTLOOK AND CONCLUSIONS

This review has shown that particle physics has already generated, in the past twenty years, a wealth of advanced technical applications in a wide variety of subjects. It has often been noted that scientists have a poor record at predicting the future of their discoveries. One would have to be very brave indeed to indicate which of the technologies outlined in the previous chapters will later shape and pervade the daily life of our grandchildren in the same way as television and computers which are legacies of past physicists.

I would, nevertheless, like to point in the direction of energy technologies. In Fig. 1 taken from a lecture given by C. Marchetti at CERN in 1980 in the Bernard Gregory Memorial cycle of lectures\textsuperscript{72)}, one can see the succession of energy technologies expressed as a function of their market share. For the next century he has already drawn a line which he dubbed mu-sion, based on the argument that all the knowledge being gathered on more or less elementary particles may one day become part of every-day life. In fact, much before an epoch which does not yet very much attract the attention of tax-payers and their governments, particle physics could play a decisive role as a new major energy source if muons could indeed catalyse nuclear fusion\textsuperscript{73)}.

![INVENTION AND INNOVATION WAVES - THE SECULAR SET](image)

**FIG. 1**

The first three waves of the series are historical. We live in the fourth. The following two are indicated to show the interlocking of the various components. In the upper part of the figure the indexed prices for energy are reported to show the precise match between energy price flaring and wave centers. By analogy one should expect a rapid fall of real price for oil in the next few years.

ACKNOWLEDGEMENTS

This paper has to a very large extent benefitted from numerous comments and suggestions from many CERN colleagues who have kindly accepted to read it. I would like to thank them here for the substantial improvements and the fruitful advice they have so given.

REFERENCES


13. D. Lambrecht.  
D. Lambrecht and L. Intichior.  


15. W. Hassenzahl.  


17. R.J. Schermer et al.  

18. R. Goodall.  

19. Y. Koytani.  


21. C.M. Rode et al.  

22. G. Claudet et al.  
Preliminary study of a superfluid helium cryogenic system for the large hadron collider. CERN/LC Note 26, June 1985.


24. I.L. McDougall, N. Heiberg, K. White  

25. J.P. Hobson.  

26. C. Benvenuti.  
Recent advances in vacuum techniques for accelerators. Proc. of the 10th Int. Conf. on cyclotrons and their applications. April 1984.

27. R. Horne et al.
   MANTIS 2: A new long range vehicle and servo master slave manipulator for the CERN complex. To be presented at the A.N.S. Conf. on remote systems handling. Pasco, Washington, April, 1987.

   Etude de l’utilité économique des contrats du CERN. CERN 75-6, June 1975.


30. G. Faillon.


33. O. Bayard.
   La nouvelle alimentation de l’aimant du synchrotron à protons du CERN. CERN/71-10, April 1971.

34. J. Fox.

35. H. Isch.

   F. Dopping.
   A pulsed power supply 100 V, 13000 A for septum magnets. CERN 70-20, July 1970.

   CERN power converter requirements and topologies for the LEP machines. Int. PCI/Motorcon’83 Conf. Geneva, April 1983.

37. P. Proudlock.

38. D.C. Fiander et al.

39. D.C. Fiander et al.

40. D. Bloess et al.

41. S. Cittolin.

42. B. Hallgren and H. Verveij.

43. Commission of European Communities.

44. Kinetics Systems Corporation.
   CAMAC system Application Briefs.

ESONE Committee (A committee regrouping European laboratories interested in High Energy Physics instrumentation and sponsored by the European Communities).
Fastbus, a modular high speed data acquisition system for high energy physics and other applications. ESONE/FB/01, May 1983.

46. H. Verveiij.

47. H. Verveiij.
Private communication.


49. M.C. Crowley-Milling.
Experience with the SPS controls system. CERN 78-09. 1979.

50. M.C. Crowley-Milling.

51. B. Carpenter, R. Cailliau.

52. B. Carpenter.
Private Communication.

53. H. Winick and A. Bienenstock.

54. M.O. Barton.

55. L.C. Teng

56. W.B. Colson and A.M. Sessler.

57. O. Barbalat.
Applications of particle accelerators. CERN internal note DIR-TECH/Note 85-1.

58. D. Pramonik.
MeV implantation for VLSI. Proceedings of the 8th Int. Conf. on the applications of accelerators in research and industry, Denton, Texas 1984.

59. J. Sivinski and D. Sloan.
The role of linear accelerators in industry. Proc. of the 8th Int. Conf. on the application of accelerators in research and industry, Denton, Texas, 1984.

60. J. McKeown.

61. G. Charpak and F. Sauli.

63. A.P. Leavons.

64. Hidac Camera. Oxford Positron systems.

65. D. Comar.

R.D. Michwa.
Positron emission tomography. Use of short lived radionuclides for neurological research. Proc. of the 8th Int. Conf. on the Applications of Accelerators in Research and Industry, Denton, Texas 1984, p. 1072.

66. H. Hyams et al.

E. Heijne.

67. W.F. Hanson.

68. J.B. Smathers et al.
Use of cyclotrons in medical research: past, present, future. Proc. of the 8th Int. Conf. on the Applications of Accelerators in Research and Industry, Denton, Texas 1984, p. 1111.

69. A.R. Smith.

70. P. Mandrillon
EULIMA Project. Private communication.

71. J.T. Lyman et al.
Charge particles stereotactic radiosurgery. Proc. of the 8th Int. Conf. on the Applications of Accelerators in Research and Industry, Denton, Texas 1984, p. 1107.

72. C. Machetti.

73. S.E. Jones.