TECHNOLOGY OF PARTICLE ACCELERATORS

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ABSTRACT
After a short review of the main families of accelerators (direct current, linear, circular), the main constituent systems of the synchrotron are described, mainly the magnet, the accelerating system, vacuum, power converters and controls. The interplay between the technical solutions and machine performance are discussed, outlining how requirements for higher performance have stimulated technology and how improved technology allow to build more performing research instruments.

1. INTRODUCTION

Technology has and is still playing a major role in scientific research. Progress in technology have always been associated with the opening of new fields of science. Examples are numerous. Nevertheless I think that it is worthwhile recalling the impact of the telescope on astronomy and of the microscope on biology.

In the same way, particle accelerators had a crucial impact on the development of atomic, nuclear and now particle physics.

In addition to their invaluable contribution to fundamental research, accelerators have found a wide array of applications. More modern accelerators are used in many fields of pure and applied research, in medicine and industry.

The technology developed for particle accelerators has even a wider spin-off and greater potential in engineering, medicine and finally in the economies of developed societies.

The development of accelerators has followed the progress in the electronics industry and several branches of electrical and mechanical engineering. It is a field which, as a few others, has benefited from an effective and fruitful collaboration between physicists and engineers, so that the design staff of modern accelerator laboratories is composed in almost equal numbers of experimental physicists and professional engineers.

This lecture will start by describing rapidly the principle of operation of the main types of particle accelerators, review the major technologies used by the present machines, their limitations and expected development and mention their present and possible applications.

2. FAMILIES OF PARTICLE ACCELERATORS

The evolution and various types of particle accelerators can best be grasped by considering the so-called Livingston plot. It records the date at which each new machine was put into operation and the maximum achieved energy.

Fig. 1 gives the initial chart of Livingston compiled in 1960, Fig. 2 is an update from 1980 while Fig. 3 is a 1990 curve made for colliders.

2.1. DC Accelerators

The technique of accelerating charge particles by allowing them to fall in vacuum through an electrostatic potential has been known for about a century in the production of X-rays and in the early work on the measurement of properties of the electrons with the first cathode-ray tubes.
In principle it was only necessary to apply these techniques at increasingly higher voltages. There are however difficulties, primarily of insulation both for the voltage producing device and for the discharge tube through which the particles pass. The tube must be of insulating material and be well evacuated not only to prevent an arc or a flow discharge but also to permit the free passage of the particles.

One of the most successful devices, still used to-day for injection into larger machine was the Cockroft-Walton accelerator. It uses a voltage multiplier circuit by which capacitors are charged in parallel and discharged in series Fig. 4). It operates on alternating current, using rectifiers to charge capacitors during one half cycle and other rectifiers to transfer the charge during the other half cycle so as to obtain a steady direct voltage.

Another type of DC accelerator is the Van de Graaf electrostatic generator developed in the 1930's, where a high voltage is produced on an insulated electrode by bodily transporting charges up to it on a moving belt Fig. 5). A refinement of the Van de Graaf accelerators allows to double or triple the effective energy. Positive ions produced at ground potential are sent through a gas channel where they pick up two electrons and become negatively charged. They are accelerated to the high voltage terminal where both electrons are stripped off, leaving a positive ion which is further accelerated down to ground potential.

2.2. Linear Accelerators

In these devices, high energy is attained by the repeated application of an accelerating force on particle travelling in a straight line.

The first machine constructed by Wideroe in 1928 consisted in a series of hollow metal drift tubes. Alternate tubes are connected to the terminals of an AC generator (Fig. 6). Particles are accelerated in the gap between two tubes and coast freely inside the field-free tube, while the voltage changes polarity. With the proper ratio of tube length to particle velocity, the ion will reach the next gap when the potentials are reversed and experience a new acceleration.

Present linear accelerators are based on the Alvarez design. The drift tubes are enclosed in a resonant HF cavity which is made to oscillate in a mode in which the electric field is longitudinal (Fig. 7). Transverse focusing is provided by small quadrupoles placed in the drift tubes.

A novel type of linear accelerator, known as the radio-frequency quadrupole (RFQ), has recently been developed. The name derives from the structure consisting in four longitudinal electrodes or vanes placed in a resonant cavity. These electrodes or vanes are shaped so as to ensure at the same time acceleration, transverse focusing and longitudinal stability (Fig. 8).

RFQ's and Alvarez linacs are mostly used as injectors for higher energy circular accelerators. However high energy electron circular machines are limited by synchrotron radiation losses and large electron linear accelerators have been built as front line machines in their own right.

Although LEP with its 27 km circumference is now the largest electron accelerator, it is likely that future electron machines will be linear and not circular colliders.

2.3. Circular Accelerators

The cyclotron designed by Lawrence in 1929 can be considered as a wrapped up Wideroe linear accelerator encased in an evacuated chamber with the addition of a steady magnetic field perpendicular to its plane. The effect of the field on the moving particles is to cause their path to become circular. The function of the drift tube is fulfilled by two semicircular hollow electrodes shaped like two half pill boxes called Dees (because of their resemblance to the
capital letter D). These are connected to a source of alternating voltage of fixed frequency as were the drift tubes in a Linac (Fig. 9).

The operation of the cyclotron depends on the fortunate circumstance that fast particles take a long path and slow particles a short one so that the time required by either is the same and the accelerating frequency can be kept constant. This can be readily explained by the equation giving the angular velocity \( \omega \) which is derived from the equation expressing the fact that, at every instant, the magnetic force \( eBv \) supplies the centripetal force \( \frac{mv^2}{r} \) required to keep the ion of mass \( m \) and charge \( e \) on an orbit of radius \( r \) in a field of strength \( B \)

\[
\frac{mv^2}{r} = eBv \quad (1)
\]

\[
\frac{v}{r} = \omega = \frac{e}{m} B \quad (2)
\]

The angular velocity is indeed independent of radius or velocity. This equation does not however hold for relativistic particles where the mass \( m \) can no more be considered constant, so cyclotrons are limited to energies of a few tens of MeV. The frequency must be modulated as the momentum of the particle increase to keep the particle synchronized, hence the name synchro-cyclotron.

In cyclotrons (and synchro-cyclotrons) the radius of the trajectory increases with energy. Large size magnets are therefore required to reach high energies. As the magnet mass rises as the cube of the radius, there is a practical limit to the energy which can be reached with this type of machines. The CERN synchro-cyclotron which is one of the largest machines of its type, reaches an energy of 600 MeV with a pole diameter of 5 m requiring a magnet weighting some 3'000 tons.

The synchrotron overcomes this difficulty by constraining the particles to rotate at a constant radius (Fig. ). The guiding magnetic field rises in step with the increasing momentum. The angular frequency and therefore the frequency of the accelerating voltage also increases with momentum; however, the frequency becomes nearly constant when the particles reach the relativistic regime.

Early synchrotrons required large vacuum chambers and therefore bulky magnets. To achieve simultaneous horizontal and vertical stability, focussing had to remain rather weak, resulting in large amplitude transverse oscillations and therefore a large beam size.

Strong focussing can only be achieved in one plane, at the expense of defocussing in the other one. However by alternating vertically and horizontally focussing sections, global strong focussing can be achieved in both planes resulting in much reduced beam size, smaller apertures and compact magnets.

The gain achieved by strong focussing synchrotrons can best be realized when noting that the CERN PS, though an early machine, was capable of reaching 25 GeV with magnets placed along a 628 m circumference for a total weight of 3000 tons equal to the weight of the magnet of the CERN 600 MeV synchro-cyclotron.

Most modern medium and high energy accelerators, storage rings and colliders follow the strong focussing synchrotron principle. One will therefore concentrate on the technology of these machines.
3. THE SYNCHROTRON

The major constituting elements of synchrotrons are the magnet system which provides the bending and focussing fields, the accelerating system often called RF system because it operates in the radio frequency range and the vacuum.

The ultimate performance of a machine is determined by the technical limits of these systems and it is to a great extend the associated engineering developments which have ensured the continuous improvements represented on the extended Livingston plots.

Depending on the type of machine, the limit originates in one or another system.

For protons (or heavy ions) the magnet system is the essential system. The final energy of a machine is determined by the radius and the magnetic field. Electron synchrotrons and colliders are limited by the available RF power to make up for the synchrotron radiation losses which increase with the fourth power of the energy.

Vacuum is crucial in storage rings and colliders since the residual pressure determines the beam life-time and finally the integrated luminosity which is the parameter of interest to the user.

Synchrotron requires in addition several important auxiliary systems which can be quite expensive in large machines. Particle source and injectors to provide the beams, power converters to drive the magnets, radio frequency or microwave power sources for the accelerating system, cryogenics to keep superconducting magnets at their required operating temperatures, controls and beam diagnostics to ensure the operation and monitor the performance are the main ones which will be briefly described.

3.1. Magnet System

Early synchrotrons like the CERN PS or the ISR had combined functions magnets with pole pieces shaped so as to provide both the bending and the focussing function. Strong focussing was achieved by alternating the orientation of the magnet gradients (hence the name AGS : Alternate Gradient Synchrotron to designate the Brookhaven proton synchrotron). Pole-face windings were foreseen on the poles to compensate the saturation distortions at high fields. They were also used to create higher order fields (sextupoles,...), to adjust the chromaticity (tune variation as a function of the radius) for stabilizing the particle motion.

In spite of additional correction magnets, it was difficult to adjust separately all the parameters. Furthermore, iron saturation was reached at the pole tip, limiting the maximum field which could be achieved on the central orbit and therefore the peak energy which could be reached by the beam.

Modern synchrotrons have separate function magnets, namely dipoles for bending, quadrupoles for focussing, sextupoles and octupoles for chromaticity control and correction of higher order fields. The dipoles which are by far the major elements of the magnet system, in terms of total size and performance, can be optimized for higher field values (above 2 T in the SPS, against 1.2 T on the central orbit of the CPS) thereby increasing the peak machine energy.

For large electron machines, such as LEP, the field requirements are modest but one must maintain the field quality and try to compensate this relaxed specification by a corresponding cost saving. This is achieved by the interspacing of the lamination by concrete layers.

Low energy machines such as for instance the Antiproton Accumulator and collector rings face another problem. They must handle a large emittance beam and have therefore a corresponding large aperture. Having to store particles over extended periods (several days) an excellent field quality must be maintained over large apertures (good field width of ~40 cm).
Superconductivity is bringing a new generation of magnets with increasing performance. The Tevatron magnets at Fermilab, have exceeded 4 T, HERA at Desy, Hamburg, operates at 6.5 T, while 10 T are aimed at for the LHC with already successful operation above 9 T of two models, one with NbTi conductors operating at 1.8 K and another with Nb3Sn at 4.5 K. The LHC magnet will have another novel feature, a two-in-one layout with two magnets of opposite polarity in the same cryostat (Fig. 10).

Synchrotron magnets present a host of technological challenges. The over-riding one is certainly field quality and reproducibility between units. Particles will circulate over millions of turns and even small errors may build up and lead to beam blow up and losses. Strong focussing synchrotrons are characterized by 'resonances'. These are regions in the tune diagram (which represents the transverse focussing) where particle trajectories are unstable; they are excited by the higher order terms of the magnetic field. A peculiar problem to superconducting magnets are 'persistent' currents, induced by the magnetic field ramping but which are not damped because of the absence of electrical resistance in the conductors. Persistent currents can be reduced if the conductor is made of thin filaments. Filaments for present magnets have diameters in the 10 to 15 m range. For future machines, like the LHC, one is aiming at 5 to preferably 2.5 m.

Another technical problem is cooling. Classical copper coil magnets have hollow conductors through which water is made to circulate to remove the resistive losses. Demineralized oxygen free water is required to avoid corrosion. This entails for large machines complex and extensive auxiliary water treatment systems. Cooling brings problems of quite another order of magnitude for superconducting magnets. The conductors must work at liquid Helium temperature to preserve the superconducting state and a complex cryogenic installation must be provided with cryostats, heat shields and an intermediate liquid nitrogen stage. For the LHC, to reach 10 T with NbTi conductors, a third stage with superfluid Helium is required.

Beside the regular lattice magnets discussed so far, synchrotrons require also special injection and ejection switching magnets with peculiar technical problems. The initial deflection towards the extracted beam channel is given by a magnet with a very fast rise time, so that the field rises from zero to its nominal value with the few tens of nanoseconds separating two successive bunches. Kicker magnets are followed by separator magnets characterized by a thin conductor, called septum, carrying a large current, designed to create a large useful field inside the magnet gap with a minimum stray field beyond so as not to perturb the circulating beam.

3.2. Accelerating Systems

The parameters of the accelerating system vary considerably depending on the type of particles to be accelerated and the energy range to be covered.

In low and medium energies protons synchrotrons such as the CERN PS and its Booster injector, the injected particles are not yet relativist and the revolution frequency of the particles varies substantially during acceleration. The chosen solution is to have ferrite loaded resonant cavities with the tune adjusted by varying the saturation of the ferrite.

In relatively small synchrotrons, the revolution time is short and even with a moderate energy gain per turn (say some 100 kV/turn) the beam is accelerated to top energy within a fraction of a second. The limit comes often more from the magnet power supply than from the acceleration system. In large accelerators the voltage gain per turn becomes a key operating parameter (for a given maximum field, the energy scales with the radius but the necessary voltage gain per turn scales with the square of the radius if one wants to keep the same acceleration time so as to give the same particle flux to the users).

Another requirement of the acceleration system is to have enough voltage to ensure phase (i.e. longitudinal) stability for a beam which has an inherent momentum spread.
On the other hand in high energy machines there is little velocity change between injection and top energy. There is no need to accommodate a large variation in the accelerating frequency and one can choose simpler and more efficient accelerating structures. For the 400 GeV SPS there is only a 0.44% velocity change and an untuned travelling wave cavity has a sufficient band-width to cover the range.

The choice of the RF frequency must take into account beam dynamics, system design and efficiency considerations. In the case of the PSB-PS-SPS complex the need to cover a wide frequency range with ferrite tuning lead to the selection of a 3 to 9.5 MHz range for the CPS (3 to 8 MHz for the PSB), while 200 MHz was the optimum choice for the SPS. For large electron accelerators and colliders which are dominated by synchrotron radiation losses, and require high power levels, RF efficiency becomes a key design element. For the first phase of LEP one has chosen a five cell copper structure coupled to a single cell storage cavity operating at 352 MHz. The idea is to store the RF power between successive bunch crossing in a reduced loss structure, with the power in the more highly dissipative accelerating structure, only during the presence of the beam.

In spite of clever designs, copper cavities driven at the power levels required by large colliders have high ohmic losses and several laboratories have developed superconducting RF cavities. The first generation was made of massive Niobium. The poor electrical conductivity of Niobium in the normal state makes these cavities very sensitive to accidental heat generation from sparking. A significant improvement is coming from the development of Niobium coated copper cavities which, because of the good conductivity of copper, are far less sensitive to these possible incidents.

The accelerating systems of modern machines have to perform complicated beam gymnastics in order to provide the flexibility required by the evolution of their operating conditions. For instance when accelerating heavy ions they must be able to achieve a larger frequency swing than with protons. This is made possible with the existing RF system by changing harmonic number during acceleration. In practice acceleration is stopped for a short moment by keeping the magnetic field constant; the beam is debunched, the RF frequency is swept back to a lower value and then retrapped on that value, when acceleration can resume. A similar problem of harmonic number change occurs between the PS and the SPS as the acceleration systems operate on different frequencies.

These examples are among the many technical problems which face the designers and machine physicists who operate and upgrade accelerators.

Control of longitudinal beam instabilities is also achieved by appropriate feedback loops or additional RF cavities operating on harmonics or subharmonics of the main drive.

The high power levels necessary for electron colliders have also stimulated the development of high efficiency RF power generators. In the case of LEP, klystrons capable of delivering 1 MW of DC RF power with an efficiency of 68% have been developed by industry.

Novel constraints on the accelerating systems have come from the multiple roles assigned to proton accelerators converted into injectors for a downstream lepton machine. They had for instance to be fitted with accelerating systems matched to the main lepton ring (namely LEP) but these cavities must be electrically short circuited when accelerating protons to avoid the induction of destabilizing voltages by the proton beam.

3.3. Vacuum

The pressure level of accelerators must first be low enough to avoid scattering of the beam by the residual gas. This was easily satisfied in the early synchrotrons by operating in the
10^{-5}/10^{-6} Torr range which could be reached with the existing technology of oil diffusion pumps. Care had already to be taken to select material with low degassing rate for the vacuum chamber such as stainless steel and to avoid mechanical construction details leading to prohibitive pump down time.

With the performance improvements of synchrotrons in the 1960's, it was discovered that even at the few 10^{-6} Torr level, intense beams would ionize sufficiently the residual gas to produce a cloud of ions which could drive instabilities leading to beam losses. This pushed the requirement an order of magnitude downward to 10^{-7}, which was achieved by replacing diffusion pumps by ion pumps and substituting metallic joints to elastomers.

Vacuum technology was influenced in a much more dramatic way by the development of the Intersecting Storage rings at CERN. They were the first proton-proton colliders and did present a number of major technical challenges to the vacuum engineers. Instead of circulating for durations of at most a few seconds as in a ring operating in the accelerator mode, beam was stored for hours without significant scattering, since even if there is no loss, the beam is blown up and the luminosity hence the number of interesting events is reduced.

Three stages of pumping were provided, turbomolecular roughing pumps, followed by sputter ion pumps and finally titanium sublimation pumps. Furthermore special care was taken to clean the vacuum chamber by glow discharge and bake out at temperatures of 250/300°C to remove the adsorbed gases.

I was thus possible to reach pressures in the range of a few 10^{-12} Torr in the arcs and below 10^{-12}Torr in the intersection regions where it is crucial to minimize the background due to collisions with the residual gas.

The construction of LEP raised new issues. The main problem is due to the constant degassing induced by the synchrotron radiation in the magnets. Furthermore the reduced beam size (compared with a proton machine) results in a vacuum chamber of rather small cross section which has therefore a small vacuum conductance. This has lead to the idea of distributed pumping with a non-evaporable getter (NEG) strip installed in a pumping channel, which is an integral part of the vacuum chamber. The NEG pump consists in a 3 cm wide constantan strip coated with an aluminium-zirconium alloy which forms stable chemical compounds with the majority of active gases. The getter can be reconditioned by heating at 400°C for some 15 minutes.

3.4. Power Converters

Particle accelerators and colliders and in particular (but not only) their magnet systems present a number of stringent powering requirements.

Synchrotrons require the regular excitation of large magnetic systems within times of the order of a few seconds or even a fraction of a second.

In the 1950's and 1960's the pulsed power could not be taken directly from the mains and large motor generator sets were used as flywheels. Progress in reactive power compensation and filtering together with the access to the grid at the 400kV level allowed in the 1970's direct pulsing from the mains but one must nevertheless ensure an accuracy and a reproducibility of the magnetic field in the 10^{-6} region.

Colliders have even greater current stability and hence regulation requirements for their power conversion system.
A large accelerator complex with its numerous beam transfer lines and its extensive experimental areas requires a considerable number of accurate and efficient power supplies with ratings ranging between a few kilowatts for corrective elements to megawatts for the main magnets. Innovative techniques such as switched mode, precision bipolar, resonant or fast pulsing units have been developed and are gaining widespread use for other applications.

The powering of fast deflectors such as kicker magnets require megawatt pulses of a few microseconds duration with rise-time in the nanosecond range, which entails suitable pulse forming network and fast high current switches which are used in all the pulsed power field.

3.5. Controls

Large accelerators have tens of thousands of components, accelerating units, magnets, power supplies, vacuum pumps and gauges, position intensity or profile monitors, timing and sequencing circuits which must be accurately programmed, controlled and synchronized over distances of several kilometres or even tens of kilometres in the case of LEP.

The information must be presented and displayed in a meaningful way to the engineers and technicians who need means of accessing and interacting with the process.

The hardwiring of the first accelerators has given way to an extensive network of process control computers linked on the one side to the process via data acquisition and distribution links with more local intelligence to reduce the transmission requirements and on the other side to complex operator consoles with what were in their time innovative man-machine interaction devices such as computer backed knobs and touch screens which have now been adopted in industrial environments or original software developments which were later taken into commercial products. With the present development of personal computers and work-stations the trend is to use commercial hardware and customize the software. The interest of the computer manufacturer for the common development of some of these applications demonstrates that there is an interest in other areas for the solutions which will be engineered.

The connection to the computer of the process to be controlled and of the elaborate monitoring and diagnostics systems requires an extensive data acquisition and control network. Expert systems are being developed to assist operation and trouble-shooting.

3.6. Other Technical Systems and Related Engineering Problems

- Beam instrumentation and diagnostics to measure beam position, beam intensity, beam transverse and longitudinal profiles, beam oscillations and instabilities, beam losses,... with high spatial and time resolution over a wide range of intensities.
- Survey to align with a precision of a fraction of a millimetre the accelerator components and the beam lines over distance in the kilometre and now tens of kilometres range. The requirements have led to the development of original instruments and methods which find applications in general surveying, geodesy and large tunnel construction such as the Channel tunnel between France and Britain.
- For antiproton collider one has developed stochastic and electron beam cooling techniques which have in turn led to several technological requirements and developments in particular in the microwave engineering field. A recent application is radar for geological research, archeological applications are also envisaged.
- The construction of accelerator components need a large variety of advanced mechanical techniques. Recent examples are for instance:
  - the metallisation of ceramic vacuum chambers for magnetron sputtering,
  - composite tubes for experimental vacuum chambers of colliders,
- Niobium coating of copper for the production of superconducting RF cavities.
- Superconducting magnets and RF cavities require sophisticated cryogenic systems. The cryogenic system of the Fermilab Tevatron consisting of a central helium liquifier coupled via liquid transfer lines to satellite refrigerators feeding strings of magnets is an example of the state of the art. Existing superconducting accelerators such as the Tevatron or machines like HERA operate with magnets at 4 K. To reach the field intensity of the planned CERN LHC a 2 K superfluid helium system is being studied. Classical colliders use superconducting focussing elements and the associated cryogenics such as cryostats and transfer lines to achieve a small beam size at the interaction point.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Subject</th>
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<tbody>
<tr>
<td>Mechanics &amp; Vacuum</td>
<td>Ultra-high vacuum (UHV)</td>
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<td></td>
<td>High precision</td>
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<tr>
<td></td>
<td>Bellows</td>
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<td></td>
<td>Secondary emission grids</td>
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<td></td>
<td>Fast wire scanner without vibrat.</td>
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<td></td>
<td>Mirror for UV synchrotron light</td>
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<td></td>
<td>Beam collimators</td>
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<td></td>
<td>Feed-throughs</td>
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<tr>
<td>High permeability amorphous magnetic material</td>
<td>Magnetic measurements</td>
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<tr>
<td>Atomic jet (laser driven)</td>
<td>Schottky pick-ups</td>
</tr>
<tr>
<td>Low-noise amplifiers &amp; cryogenics applied to</td>
<td>Light amplification. For ultra-high vac.</td>
</tr>
<tr>
<td>front-end electronics</td>
<td>(bakeable at 300° C)</td>
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<tr>
<td>Micro-channel detectors</td>
<td>Optical auto-correlator</td>
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<tr>
<td>Monolithic circuits</td>
<td></td>
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<tr>
<td>Low price (L.P.)</td>
<td>Radiation measurements</td>
</tr>
<tr>
<td>High performance (H.P.)</td>
<td>L.P., H.P., R.R. TV cameras</td>
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<tr>
<td>and/or radiation resistance (R.R.)</td>
<td>L.P., H.P. fast ADC</td>
</tr>
<tr>
<td>components or circuits</td>
<td>H.P. Pico-amperemetre</td>
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<tr>
<td></td>
<td>Position sensitive electron multiplier</td>
</tr>
<tr>
<td></td>
<td>(H.R., R.R.)</td>
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<tr>
<td></td>
<td>Double sided strip detector</td>
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<td>for UHV</td>
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<td>R.R. TV screens</td>
</tr>
<tr>
<td></td>
<td>H.P. low charge integrator</td>
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<tr>
<td></td>
<td>H.P. differential discriminator</td>
</tr>
<tr>
<td>Laser</td>
<td>Short pulse, high power</td>
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<tr>
<td>Picosecond analysis</td>
<td>Streak camera</td>
</tr>
<tr>
<td>Microwave</td>
<td>Wide-band amplifier (7 GHz)</td>
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<tr>
<td></td>
<td>for photo diode</td>
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<tr>
<td>Optical fibres</td>
<td>Directional coupler</td>
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<td></td>
<td>Optical fibre ring</td>
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<td>Beam imaging</td>
<td>Multi-channel PM analysis</td>
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<td>ccd (charged coupled device) anal.</td>
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<tr>
<td></td>
<td>Stroboscopic reading of a CCD</td>
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- High voltage electric separators were used in the earlier days of particle physics to separate particles in secondary beams. Similar devices with synchronous switches are now used inside colliders to separate beams of opposite polarities when collisions are not wanted, during the injection and acceleration phases and in intersections not equipped with detectors so as to avoid the beam-beam phenomena which reduce luminosity.

- The design of a large collider involves a huge amount of elements. In the 27 km long LEP tunnel, one finds about 60,000 different components of various dimensions ranging from some millimetres to kilometres and summarized in the table below.

<table>
<thead>
<tr>
<th>Accelerator Systems</th>
<th>Number of diff. components</th>
<th>Total number of components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Civil engineering</td>
<td>40</td>
<td>120</td>
</tr>
<tr>
<td>Magnets and RF system</td>
<td>40</td>
<td>5000</td>
</tr>
<tr>
<td>Beam instrumentation</td>
<td>30</td>
<td>620</td>
</tr>
<tr>
<td>Vacuum system</td>
<td>220</td>
<td>15,240</td>
</tr>
<tr>
<td>Accelerator support</td>
<td>100</td>
<td>5,500</td>
</tr>
<tr>
<td>Water cooling</td>
<td>330</td>
<td>14,900</td>
</tr>
<tr>
<td>Electrical distribution</td>
<td>110</td>
<td>13,700</td>
</tr>
<tr>
<td>Transport (monorail)</td>
<td>25</td>
<td>1,700</td>
</tr>
<tr>
<td>Survey</td>
<td>10</td>
<td>780</td>
</tr>
<tr>
<td>Total</td>
<td>905</td>
<td>57,560</td>
</tr>
</tbody>
</table>

It is therefore not surprising to realize that computer aided design is now an essential design tool for such a project and that the logistics of its installation is a major engineering undertaking.

- Some accelerator components, in particular the particle-antiparticle production targets and the nearby equipment, become heavily irradiated in the course of their operation and one requires sophisticated remote handling devices for their maintenance and replacement.

4. CONCLUSION

The particle accelerators developed for fundamental physics research have required the development of numerous and ingenious technical systems. Accelerators are now widely used outside their field of origin, in many other areas of research such as condensed matter, surface science, semiconductors, chemistry, biology, archeology,.... They also have applications in medicine both for diagnostics and therapy and in many industrial fields from ion implantation for semiconductor manufacture to radiation processing for food stuff preservation.

The technologies developed for particle accelerators may have even more important applications in the coming century. Superconductivity will certainly play a crucial role in power engineering for future fusion generators, electricity transport through lossless cables or storage in large coils in the form of magnetic energy. Superconductivity may also have many applications in the transportation sector (levitated trains, marine propulsion). Availability of large capacity memories (Gigabit range) and complex integrated circuits manufactured by microlithography with synchrotron radiation light will allow the use of computer for many commercial and domestic applications.

NMR using superconducting magnets, a spin-off of synchrotron technology is already a powerful medical imaging diagnostic tool. This technique has furthermore the potential not only to detect tumours and other physical anomalies but also to monitor the metabolism and allow early detection of potentially harmful disorders.
It is impossible to predict which of these possible technologies will have the greatest impact but if one judges from the success of 19th century accelerator technology now used everywhere in TV tubes, it needs no excessive boldness to envisage an even wider spread of accelerator derived technologies in the future.

REFERENCES and BIBLIOGRAPHY

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- The 1980 updated chart was published by L.C. Teng in the Proceedings of the 11th International Conference on high Energy Accelerators held at CERN in July 1980.

- The 1990 projection for colliders has been prepared by G. Brianti.

- Schematics of the various types of accelerators are taken from 'Principles of cyclic particle accelerators' by J. Livingwood, Van Nostrand, 1961 and from the already mentioned book by Livingston and Blewett.

- The schematic of the RFQ is from an unpublished lecture by M. Weiss.

- The table on the technologies associated with beam diagnostics is adapted from L. Burnod.

- The list of LEP components is taken from a report by G. Bachy.

- The technology of particle accelerators is described in several types of documents:
  - The design report for a new project (PS Booster, ISR, Antiproton Accumulator, LEP, LEAR,...).
  - Specialized reports on the various systems presented at accelerators Conferences.
  - Technical brochures on a given machine published by laboratories, usually for the inauguration of the project.
  - The CERN Accelerator School has included in some of its courses lectures on specialized accelerator sub-systems (magnet, RF, ion sources,...) and organized schools on particular technological topics associated with accelerators such as geodesy or power converters.
Fig. 1: Energies achieved by accelerators from 1930 to 1960. The linear envelope of the individual curves shows an average tenfold increase in energy every six years.

Fig. 2: The Livingston chart -- accelerator energy versus year of completion
19 OCR Output

(a) Corkcroft-Walton voltage-multiplying circuit. (b) Accelerating tube for 0.7-Mev positive ions.
Fig. 5: Schematic diagram of generator enclosed in a grounded pressure tank. Circuits are shown for spraying charge on both the ascending and descending faces of the belt.

Fig. 6: The Wideröe linear accelerator. Each drift tube becomes charged to the opposite sign from that of its neighbors. The distance from gap to gap is traveled in a half-period of the oscillator.
Fig. 7: The Alvarez linear accelerator. All drift tubes become simultaneously polarized in the same direction because of the electric field in the resonant cylinder. The distance from gap to gap is traveled in a full period of the oscillator.

Fig. 8: RFQ Schematic

Approximate dimensions: L = 140 cm, D = 35 cm
Beam region: d ≤ 12 mm, around ± axis
Fig. 9: Schematic drawing of early cyclotron with dees supported on glass insulators and resonating with a lumped inductance. The ion source is a simple hot filament. The external deflector directs the projectiles into a re-entrant bombardment chamber.

Fig. 10: Proton Synchrotron of four sectors