Elementary particles

THIRD EDITION

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1.1 Introduction

An important part of the study of particle physics is an understanding of experimental tools – the accelerators, beams and detectors by means of which particles are accelerated, their trajectories controlled and their properties measured. There exist a limited number of types of accelerators and detectors in common use or which have in the past proved crucial to the progress of the subject. No more technical detail is included here than is essential to an understanding of the uses of these techniques in the study of particle physics. In the chapters which follow we shall assume that these techniques are familiar to the student, so that it will generally not be necessary to describe in detail the technique used in particular experiments.

1.2 Particle accelerators and beams

1.2.1 *Introduction*

Particle accelerators and their associated external beam lines are key elements in most particle physics experiments.

Charged particles are accelerated by passing across a region of potential difference which in practice is normally a cavity fed with radiofrequency power and phased such that the particle is *accelerated* as it passes through. Since practicable fields and dimensions are such that a single passage through the cavity can produce only a rather small acceleration, the particle must either pass through many such cavities or pass many times through the same group of cavities by guidance around a cyclic path.

In the *linear accelerator* a linear RF structure is fed with RF power from a bank of klystrons to produce a wave travelling down the structure with a velocity equal to the particle velocity so that the particle remains always on the accelerating phase of the wave throughout its flight. The largest operational linear accelerator is the two-mile-long accelerator at Stanford Linear Accelerator Centre (SLAC) which accelerates electrons to 50 GeV.

In *cyclic accelerators* a magnetic field is used to guide the particles around a cyclic path such that they repeatedly pass across the accelerating gap. In the *cyclotron*, which was an important machine in the early days of the subject, protons or heavier charged particles moved in a vacuum box containing two hollow D-shaped cavities between which could be applied an alternating potential difference (fig. 1.1). The magnetic guide field normal to the plane of the Ds caused particles of constant momentum to travel in a circular orbit of radius R, given by

$$R = \frac{pc}{Be} \quad p = \text{momentum}$$

$$e = \text{charge}$$
$$B = \text{magnetic field.}$$

The frequency of the potential difference applied to the gap between the Ds must be such that particles are accelerated each time they cross the gap.

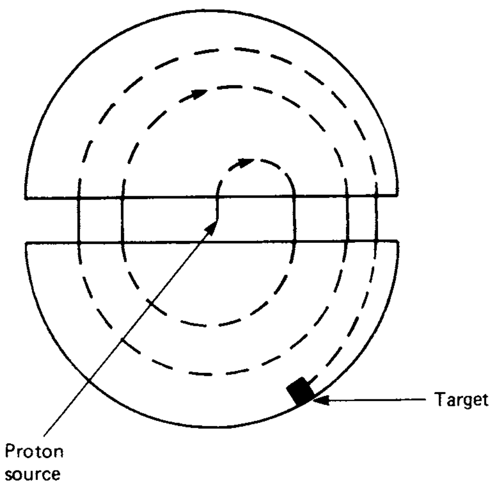


Fig. 1.1. Principle of operation of the cyclotron.

The angular frequency is easily seen to be given by

$$\omega = \frac{Be}{mc} \quad m = \text{particle mass}$$

which is independent of the particle momentum as long as the mass is constant. For high energies, of course, the mass increases due to the relativistic effect and a constant frequency is no longer adequate.

In the *synchrotron*, particles are maintained at *constant radius* in a ring-shaped vacuum chamber contained in a magnetic field. The magnet is thus also in the form of a ring and need not cover the whole circular area as in the cyclotron. Since the radius of the orbit is constant, the magnetic field must increase to hold the particles in the same orbit as their momentum increases. The circulating frequency at any moment is then given by

$$\omega_0 = \frac{Bec}{E} \quad E = \text{total particle energy.}$$

Acceleration is achieved by having the particles pass through suitably-phased RF cavities at one or more positions in the ring. In practice, the particles are always bunched in the accelerator, although several bunches may be present at the same time. In all high-energy machines the particles are first accelerated in a linear accelerator before injection to the synchrotron. For electrons, which become relativistic at very low energy, the velocity and thus the accelerating frequency is essentially constant. For protons this is not so.

1.2.2 *Colliding beams and available energy in the centre of mass*

When a particle of rest mass m and total energy E collides with another particle of the same mass at rest the energy available in the centre of mass of the two particles is (see appendix A) E' given by

$$E'^2 = s = 2m^2 + 2mE.$$

Thus at high energies where $E \gg m$ the energy available in the centre of mass increases only as the square root of the particle energy E, with much of the total energy going to increase of the velocity of the complete centre-of-mass system (cms). In order to obtain the very high energies in the cms necessary, for instance, to make very heavy particles like the W and Z, the energy for a *fixed-target* machine thus becomes very great. For two particles of equal mass and equal and opposite momentum, however, the centre-of-mass frame is the same as the laboratory frame and the energy available is simply $2E$. Thus for two 50 GeV particles colliding head-on we have 100 GeV available in the centre of mass, whereas to achieve this result in a fixed-target collision would require an accelerated proton to have an energy $\sim$ 5000 GeV.

Practical limits on attainable magnetic fields (presently up to $\sim$ 6–7 T with superconducting magnets) and on ring radius have led to colliding-beam machines as the favoured way to attain the highest energies. For particles of opposite electric charge, such as electrons and positrons or protons and antiprotons, both beams can be accelerated as bunches circulating in opposite directions in the same vacuum chamber and colliding at the intersection positions where experiments are placed. For particles of the same charge, separate but intersecting rings are necessary.

In order to achieve an adequate rate of interactions the number of incident particles and the target density in a fixed-target machine must be sufficiently high. The number of interactions is approximately (for a 'thin' target)

$$N_I = N_P \cdot N_T \cdot n \cdot \sigma \qquad \begin{aligned} N_I &= \text{no. of interactions/second} \\ N_P &= \text{no. of incident particles/pulse} \\ N_T &= \text{no. of target particles/unit area} \\ \sigma &= \text{interaction cross-section} \\ n &= \text{no. of pulses/second} \end{aligned}$$

$$N_T = \frac{N_A}{A} \rho \cdot t \cdot N \qquad \begin{aligned} N_A &= \text{Avogadro's number} \\ A &= \text{atomic weight} \\ \rho &= \text{target density} \\ t &= \text{target thickness} \\ N &= \text{no. of target particles/atom.} \end{aligned}$$

We are often interested in processes with very small cross-sections $\sim$ few nanobarns (10^{-33} cm^2). A typical fixed-target experiment using a 1 m-long liquid-hydrogen target bombarded with 10^7 particles per pulse every 10 seconds will yield $\sim 4 \times 10^{-4}$ interactions per second for each nanobarn of cross-section with $N_P \cdot N_T \cdot n \sim 4 \times 10^{31}$. The full circulating beam $\sim 10^{13}$ particles per pulse will yield $\sim$ 40 interactions s^{-1} nb^{-1}, but such fluxes are seldom usable in experiments.

For two colliding beams the reaction rate is customarily written in terms of the 'luminosity' L. Thus the number of interactions per unit time is

$$N_I = L\sigma.$$

The luminosity is then simply

$$L = \frac{n_1 n_2}{a} \cdot b \cdot f \quad \begin{aligned} n_1, n_2 &= \text{no. of particles/bunch in each beam} \\ a &= \text{cross-sectional area of beams at intersection (total overlap assumed)} \\ b &= \text{no. of bunches/beam} \\ f &= \text{revolution frequency.} \end{aligned}$$

Luminosities $\sim 10^{30}$–10^{31} cm^{-2} s^{-1} have been achieved or are anticipated in colliding beam machines yielding raw (unselected) rates $N_I \sim 10^{-3}$–10^{-2} interactions per nanobarn per second. Thus, perhaps surprisingly, accelerator technology has produced beams of intensity such that colliding-beam machines can produce highly-useful interaction rates.

1.2.3 *Beam stability and accelerator magnet configurations*

In a high-energy accelerator such as the CERN Super Proton Synchrotron (SPS), the protons will orbit the ring 10^5–10^6 times covering a total distance of over a million kilometres. In order to retain the beam over the complete cycle it is essential that the structure of the guiding magnetic lattice be such that the beam is not allowed progressively to defocus and that instabilities are controlled. In particular, cyclic instabilities which would add to the deviation of particles from the stable orbit progressively on each orbit must be avoided. The focusing properties of the magnet system are thus crucial parameters in the machine design.

Particles may stray from the perfect situation by deviating radially or perpendicularly from the stable orbit – transverse or betatron oscillations, and also by deviation from the ideal phase with respect to the RF acceleration – synchrotron oscillations.

To control radial and vertical deviations from the equilibrium orbit requires a non-uniform magnetic field which will focus the particle beam as does a lens in an optical system. *Quadrupole* magnets are the most commonly used magnetic focusing devices. A cross-section through a quadrupole magnet is shown in fig. 1.2. On-axis particles are unaffected by such a magnet. In the plane *AB*, off-axis particles are deflected back towards the axis so that in this plane the quadrupole acts as a convergent lens. In the orthogonal plane, however, particles are deflected off-axis and the equivalent lens is divergent. Convergence in both planes can be achieved by a combination of two or more quadrupole magnets.

In earlier generations of machines it was customary to combine the functions of bending and focusing the particles in the same magnets by shaping the poles to produce the appropriate field shape. Latterly, the practice has been to separate the bending and focusing functions by using simple dipoles for bending and separate quadrupoles (plus some more complex magnets) for focusing.

In earlier machines the betatron oscillations were of magnitude such as to require large vacuum chambers with consequent need for large-aperture magnets of high cost. For stable radial betatron oscillations the condition is that the vertical (i.e. normal to the orbit plane) component of the magnetic field should vary as r^{-n} with $0 < n < 1$. The frequencies of the vertical and horizontal oscillations are then given respectively by

$$\nu_V = \omega_0 n^{\frac{1}{2}} \quad \text{and} \quad \nu_H = \omega_0(1-n)^{\frac{1}{2}}$$

where ω_0 is the circulating frequency as already defined. The amplitude of

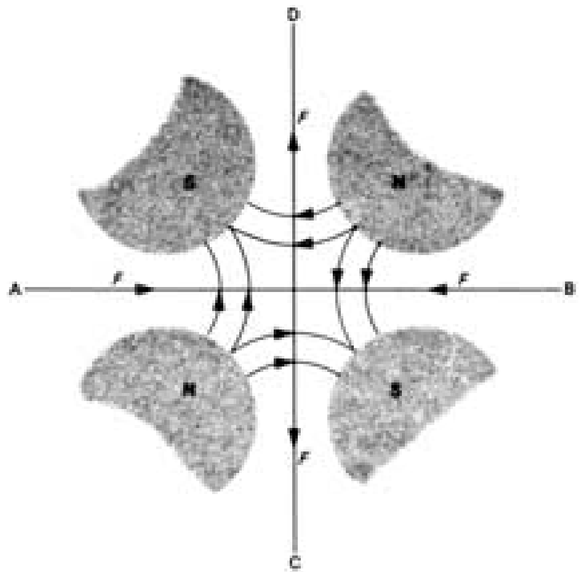


Fig. 1.2. Diagrammatic cross-section through a quadrupole magnet. The field is as shown. Negative particles passing normally into the plane of the paper from above will suffer forces F as shown. Thus the quadrupole focuses such particles in the plane AB and defocuses in the plane CD.

the vertical oscillation is, on the other hand, proportional to $n^{-\frac{1}{2}}$ so that a high value of n is required to minimise the size of the vacuum chamber and thus the magnet aperture. The *strong-focusing* idea proposed by Courant, Livingston and Snyder (1952) has proved to provide the best solution to the focusing problem. A high value of n is used to minimise the aperture but the sign of n is reversed in alternate magnets. Thus a typical configuration for a unit of a separated function machine is of the FODO variety:

Focusing (quadrupole) – No focus (dipole) – Defocusing (quadrupole) – No focus (dipole)

Focusing in one plane is accompanied by defocusing in the other but with *overall* focusing in both planes.

The synchrotron oscillations arise from the fact that a particle arriving early can be arranged to see a higher accelerating field than that for the synchronous particle. Such an early particle takes up a slightly larger radius orbit thus taking longer to circulate back to the cavity. Particles arriving late experience the opposite effect, so that particles execute oscillations about the synchronous position for the bunch.

An important development critical to the success of $\bar{p}p$ colliders has been the invention and implementation of the idea of *stochastic cooling* (Van der Meer, 1972). Antiprotons produced in collisions of protons with a fixed target will have a substantial spread in angles and energies. In order to accelerate the antiprotons with minimum loss, however, the spread in energy and direction must be small. The useful flux of antiprotons can be maximised if they can be 'cooled', i.e. made as uniform as possible in all components of momentum. The stochastic cooling method is to store the antiprotons in a ring at relatively low energy and to use pick-up electrodes to sense the particle position relative to the mean. Signals from particles off the mean are then sent across the ring and are used to correct the off-mean particles. The beam may be thus cooled before being injected into the main accelerator.

1.2.4 *Synchrotron radiation*

A charged particle which suffers acceleration emits electromagnetic radiation. Thus particles moving in a circular orbit in an accelerator will lose energy by such radiation. For a particle travelling in a circle the energy loss per turn due to synchrotron radiation is given by

$$\Delta E = \frac{4\pi}{3} e^2 \beta^3 \frac{1}{R}\left(\frac{E}{mc^2}\right)^4$$

$$= \frac{4\pi}{3}\left(\frac{e^2}{mc^2}\right) mc^2 \beta^3 \frac{1}{R}\left(\frac{E}{mc^2}\right)^4$$

$$= \frac{4\pi}{3}\left(\frac{r_e}{R}\right) mc^2 \beta^3 \left(\frac{E}{mc^2}\right)^4$$

$$= 8.856 \times 10^{-2}\left(\frac{E^4}{R}\right)$$

e = charge
β = velocity/c
E = total energy
m = mass
R = orbit radius
r_e = classical electron radius

where ΔE is in MeV, E is in GeV and R is in metres.

The m^{-4} factor means that the effect is much more important for electrons than for protons and, in practice, up to energies presently attained, it is only for electrons that synchrotron radiation is an important consideration in the accelerator design. Due to the E^4 factor the effect very rapidly becomes serious at higher energies, although some easement of the problem can be achieved by increasing R. In the LEP e^+–e^- collider at CERN the average radius is 4.2 km and at 55 GeV the synchrotron radiation loss is 260 MeV per turn (orbit is not quite circular). For energies much higher than 150–200 GeV it seems likely that in a circular electron accelerator synchrotron radiation would be such as to require unacceptable RF power compensation and that linear accelerators will be the only possibility.

1.2.5 *An example of an operating accelerator – the CERN Super Proton Synchrotron (SPS) and the LEP e^+–e^- collider*

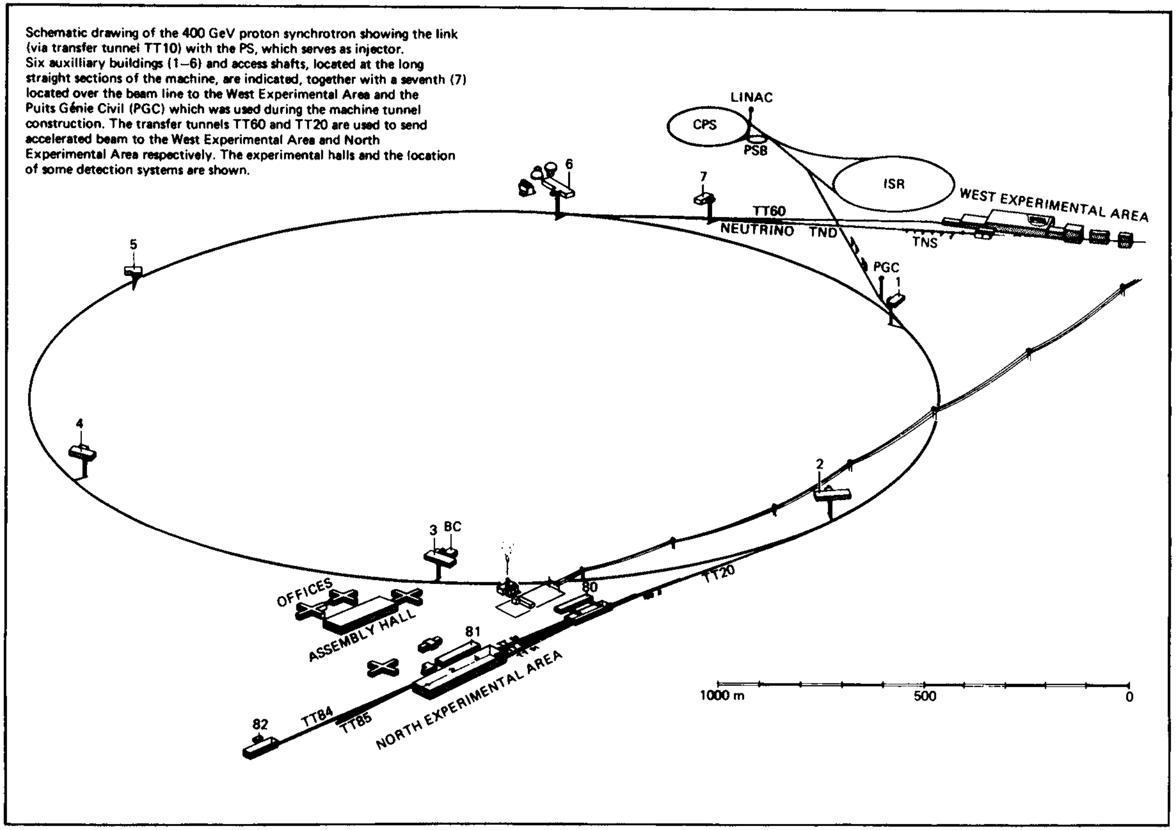
The CERN SPS, which started operating in 1976, is a proton accelerator with a maximum energy of 450 GeV which is also operated as a proton-antiproton collider at energies of 315 GeV in each beam. The layout of the machine and its injectors and experimental halls is shown in fig. 1.3(a) and some of the most important parameters of the accelerator are given in table 1.1.

The main SPS ring is housed in a tunnel of diameter 4.14 m bored in the molasse rock. There are six straight sections for injection, extraction and RF acceleration. The average bending radius is ~ 1.48 km and bending is provided by 744 dipole magnets with a peak field of 2 T. The accelerator uses a strong focusing, separated-function magnet lattice of the type: focus-bend–defocus–bend

{(quad)–(4 dipoles)–(quad)–(4 dipoles)}

(FODO) repeated 108 times round the ring. The vacuum chamber is of stainless steel with elliptical cross-section. Acceleration is achieved with

Fig. 1.3(a). Layout of the SPS accelerator and its associated facilities at CERN.



two sets of RF cavities operating at about 200 MHz. Since protons are injected into the main ring at 10 GeV the required frequency swing during acceleration is only 0.5%.

The protons are initially accelerated by a radio frequency quadrupole then transferred to a proton linear accelerator which takes them to 50 MeV. Further acceleration to ~ 800 MeV in the proton booster rings and 10 GeV in the proton synchrotron is needed before injection to the SPS ring.

In fixed-target operation protons can be extracted in either 'fast' (few μs) or 'slow' (2*s*) spills. The first is suited to bubble chamber operation where the beam should be confined to a limited time at or near the bottom of the pressure pulse providing a well-controlled time for bubble growth while the second is suited to counter experiments where a long beam spill allows the maximum number of interactions with minimum dead time for the detection system. Two experimental halls are fed with extracted beams of a remarkable variety of energies and spills on a repetition rate at maximum energy of about ten seconds. Circulating beam currents have been steadily improved throughout the life of the machine and 2×10^{13} protons per pulse is regularly achieved.

The SPS has also been used with great success as a proton–antiproton colliding ring. The antiprotons are produced in the CPS (CERN Proton Synchrotron) by protons accelerated to 26 GeV and focused onto a tungsten target. Antiprotons having energies around the production maximum of 3.5 GeV are collected and transferred to an 'antiproton-

Table 1.1. *The CERN SPS parameters*

Peak energy	450 GeV
Machine diameter	2.2 km
Injection energy	10 GeV
Magnet field (peak energy)	1.8 T
Magnet field (injection)	0.045 T
Total number of bending magnets	744
Apertures	39×129 mm^2 52×92 mm^2
Number of quadrupoles	216
Total peak voltage (bending magnets)	24.3 kV
Peak current (bending magnets)	4900 A
Number of RF cavities	2
Interaction length of cavity	20.196 m
Maximum power per cavity	500 kW
Frequency swing	0.44%
Design pressure	3×10^{-7} torr

accumulator' ring which has a large aperture and fixed field. In order to achieve the required antiproton flux it is necessary to accept particles having a certain spread in vector momentum. In the accumulator this spread is reduced by a process of 'stochastic cooling' developed at CERN by S. Van der Meer. Signals from pick-up electrodes in the ring measure the deviations in antiproton momentum from the mean value. These signals are sent across the accumulator ring to generate correction signals applied to the same antiprotons as they pass so that the spread in momentum is progressively reduced until the stack is sufficiently homogeneous for the subsequent stages of acceleration. The antiproton bunch is then ejected back into the CPS for acceleration to 26 GeV and then transferred to the SPS where three bunches of protons have already been injected and are coasting at 26 GeV in the opposite direction. Two further $\bar{p}$ bunches are injected and $\bar{p}$ and p are then simultaneously accelerated to 315 GeV/c. Since in the storage mode the bending magnets must be continuously powered they are not generally run at as high a field as in pulsed operation so that the operating energy is lower. Collisions between the $\bar{p}$ and p bunches take place in the six underground caves for experiments. Luminosities of 3×10^{30} cm^{-2} s^{-1} have been achieved with beam lifetime between fills $\sim$ 12 hours.

In summer of 1989 there was completed at CERN a large electron–positron collider, LEP. Since the e^+ and e^- are oppositely charged they can circulate in bunches travelling in opposite directions within the same vacuum chamber which consists of a ring with eight straight sections linked by eight arcs. The particles are guided by 3368 dipole magnets and focused by 808 quadrupoles the total path length around the ring being some 27 km. The ring is situated in a tunnel crossing the French–Swiss frontier and lying largely beneath the plain between the West end of the Lake of Geneva and the Jura mountains. In four of the straight sections underground halls house elaborate detector facilities while two of the remaining straights accommodate the RF accelerating cavities. Sufficient RF cavities have been initially commissioned to accelerate each beam to 55 GeV while at a later stage it is planned to increase the RF installation to reach 100 GeV in each beam. Luminosity of 10^{31} cm^{-2} s^{-1} appears to be well within reach with four bunches colliding every 22 μs in each of the experiments.

The injection system for LEP has to provide fills of positrons and electrons at intervals of a few hours depending on the beam lifetime in LEP where bunches are gradually degraded by scattering on residual gas even though the vacuum in the ring is very good ($\sim 10^{-9}$ torr). The