4
Accelerators

The 'microscopes' of the particle physicist are enormous particle accelerators.

American Institute of Physics

Accelerators are in use in many different fields, such as particle accelerators in nuclear and elementary particle physics, in nuclear medicine for tumour treatment, in material science, e.g. in the study of elemental composition of alloys, and in food preservation. Here we will be mainly concerned with accelerators for particle physics experiments [1–5]. Other applications of particle accelerators are discussed in Chapter 16.

Historically Röntgen's X-ray cathode-ray tube was an accelerator for electrons which were accelerated in a static electric field up to several keV. With electrostatic fields one can accelerate charged particles up to the several-MeV range.

In present-day accelerators for particle physics experiments much higher energies are required. The particles which are accelerated must be charged, such as electrons, protons or heavier ions. In some cases – in particular for colliders – also antiparticles are required. Such particles like positrons or antiprotons can be produced in interactions of electrons or protons. After identification and momentum selection they are then transferred into the accelerator system [6].

Accelerators can be linear or circular. *Linear accelerators* (Fig. 4.1) are mostly used as injectors for *synchrotrons*, where the magnetic guiding field is increased in a synchronous fashion with the increasing momentum so that the particle can stay on the same orbit. The guiding field is provided by magnetic dipoles where the Lorentz force keeps the particles on track. Magnetic quadrupoles provide a focussing of the beam. Since quadrupoles focus the beam in only one direction and defocus it in the perpendicular direction, one has to use pairs of quadrupoles to

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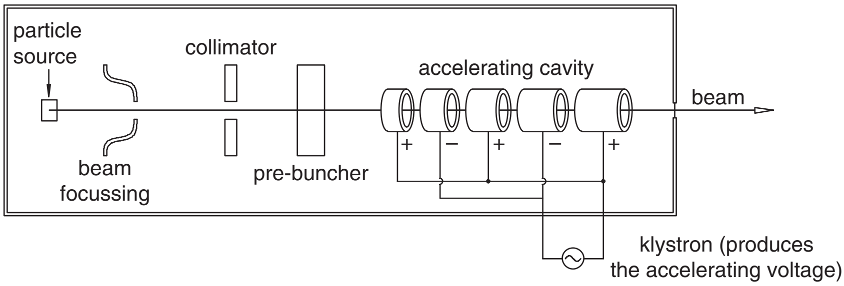

Fig. 4.1. Sketch of a linear accelerator. Particles emitted from the source are focussed and collimated. The continuous particle flow from the source is transformed into a discontinuous bunched beam which is steered into an accelerating cavity. The cavity is powered by a klystron.

achieve an overall focussing effect. The particles gain their energy in cavities which are fed by a radiofrequency generation (e.g. klystrons), which means that they are accelerated in an alternating electromagnetic field. *Field gradients* of more than 10 MeV/m can be achieved. Since the particles propagate on a circular orbit, they see the accelerating gradient on every revolution and thereby can achieve high energies. In addition to dipoles and quadrupoles there are usually also sextupoles and correction coils for beam steering. Position and beam-loss monitors are required for beam diagnostics, adjustments and control (Fig. 4.2). It almost goes without saying that the particles have to travel in an evacuated beam pipe, so that they do not lose energy by ionising collisions with gas molecules.

The maximum energy which can be achieved for protons is presently limited by the magnetic guiding field strength in synchrotrons and available resources. The use of large bending radii and superconducting

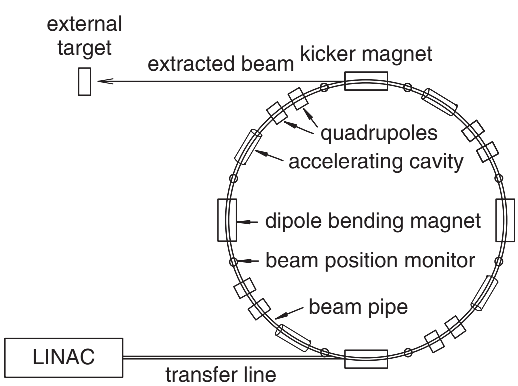

Fig. 4.2. Schematic layout of a synchrotron; LINAC – linear accelerator. The kicker magnet extracts the particle beam from the synchrotron.

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magnets has allowed to accelerate and store protons up to the 10 TeV region.

Such energies can never be obtained in electron synchrotrons, because the light electrons lose their energy by the emission of synchrotron radiation (for synchrotron energy loss, see Sect. 1.1.10). This energy loss is proportional to γ^4/ρ^2, where γ is the Lorentz factor of the electrons and ρ the bending radius in the dipoles. Only because of their high mass this energy-loss mechanism is negligible for protons. If one wants to accelerate electrons beyond the 100 GeV range, one therefore has to use linear accelerators. With present-day technology a linear accelerator for electrons with a maximum beam energy of several hundred giga-electron-volts must have a length of $\approx 15\,\mathrm{km}$, so that a linear e^+e^- collider would have a total length of $\approx 30\,\mathrm{km}$ [7].

In the past particle physics experiments were mostly performed in the *fixed-target mode*. In this case the accelerated particle is ejected from the synchrotron and steered into a fixed target, where the target particles except for the Fermi motion are at rest. The advantage of this technique is that almost any material can be used as target. With the target density also the interaction probability can be controlled. The disadvantage is that most of the kinetic energy of the projectile cannot be used for particle production since the centre-of-mass energy for the collision is relatively low. If $q_p = (E_{\mathrm{lab}}, \vec{p}_{\mathrm{lab}})$ and $q_{\mathrm{target}} = (m_p, 0)$ are the four-momenta of the accelerated proton and the proton of the target, respectively, the centre-of-mass energy $\sqrt{s}$ in a collision with a target proton at rest is worked out to be

$$s = (q_p + q_{\mathrm{target}})^2 = E_{\mathrm{lab}}^2 + 2m_p E_{\mathrm{lab}} + m_p^2 - p_{\mathrm{lab}}^2 = 2m_p E_{\mathrm{lab}} + 2m_p^2 \ . \quad (4.1)$$

Since for high energies

$$m_p \ll E_{\mathrm{lab}} \ , \quad (4.2)$$

one has

$$\sqrt{s} = \sqrt{2m_p E_{\mathrm{lab}}} \ . \quad (4.3)$$

For a 1 TeV proton beam on a proton target only 43 GeV are available in the centre-of-mass system. The high proton energy is used to a large extent to transfer momentum in the longitudinal direction.

This is quite in contrast to colliders, where one has counterrotating beams of equal energy but opposite momentum. In this case the centre-of-mass energy is obtained from

$$s = (q_1 + q_2)^2 = (E_1 + E_2)^2 - |\vec{p}_1 + \vec{p}_2|^2 \ , \quad (4.4)$$

where q_1, q_2 are the four-momenta of the colliding particles. If the beams are of the same energy – when they travel in the same beam pipe such as

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in *particle–antiparticle colliders* this is always true – and if $\vec{p}_2 = -\vec{p}_1$, one gets

$$s = 4\,E^2 \tag{4.5}$$

or

$$\sqrt{s} = 2\,E \ . \tag{4.6}$$

In this case the full energy of the beams is made available for particle production. These conditions are used in *proton–antiproton* or *electron–positron colliders*. It is also possible to achieve this approximately for pp or e^-e^- collisions, however, at the expense of having to use two vacuum beam pipes, because in this case the colliding beams of equal charge must travel in opposite directions while in $p\bar{p}$ and e^+e^- machines both particle types can propagate in opposite directions in the same beam pipe. There is, however, one difference between pp or e^-e^- colliders on the one hand and $p\bar{p}$ or e^+e^- machines on the other hand: because of baryon- and lepton-number conservation the beam particles from pp or e^-e^- colliders – or equivalent baryonic or leptonic states – will also be present in the final state, so that not the full centre-of-mass energy is made available for particle production. For e^+e^- colliders one has also the advantage that the final-state particle production starts from a *well-defined quantum state*.

If particles other than protons or electrons are required as beam particles, they must first be made in collisions. Pions and kaons and other strongly interacting particles are usually produced in proton–nucleon collisions, where the secondary particles are momentum selected and identified. Secondary pion beams can also provide muons in their decay ($\pi^+ \to \mu^+ + \nu_\mu$). At high enough energies these muons can even be transferred into a collider ring thereby making $\mu^+\mu^-$ collisions feasible. *Muon colliders* have the advantage over electron–positron colliders that – due to their higher mass – they suffer much less synchrotron-radiation energy loss.

In high flux proton accelerators substantial neutrino fluxes can be provided which allow a study of neutrino interactions. Muon colliders also lead to intense neutrino fluxes in their decay which can be used in *neutrino factories*.

Almost all types of long-lived particles (π, K, Λ, Σ, $\ldots$) can be prepared for secondary fixed-target beams. In electron machines photons can be produced by bremsstrahlung allowing the possibility of $\gamma\gamma$ colliders as byproduct of linear e^+e^- colliders.

An important parameter in accelerator experiments is the number of events that one can expect for a particular reaction. For fixed-target experiments the *interaction rate* ϕ depends on the rate of beam particles n hitting the target, the cross section for the reaction under study, σ, and the target thickness d according to

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$$\phi = \sigma \cdot N_{\mathrm{A}}\ [\mathrm{mol}^{-1}]/\mathrm{g} \cdot \varrho \cdot n \cdot d\ \{\mathrm{s}^{-1}\}\ , \tag{4.7}$$

where σ is the cross section per nucleon, N_{A} Avogadro's number, d the target thickness (in cm), and ϱ the density of the target material (in g/cm^3). Equation (4.7) can be rewritten as

$$\phi = \sigma L\ , \tag{4.8}$$

where L is called *luminosity*.

In collider experiments the situation is more complicated. Here one beam represents the target for the other. The interaction rate in this case is related to the luminosity of the collider which is a measure of the number of particles per cm^2 and s. If N_1 and N_2 are the numbers of particles in the colliding beams and σ_x and σ_y are the transverse beam dimensions, the luminosity L is related to these parameters by

$$L \propto \frac{N_1 N_2}{\sigma_x \sigma_y}\ . \tag{4.9}$$

It is relatively easy to determine N_1 and N_2. The measurement of the transverse beam size is more difficult. For a high interaction rate the two particle beams must of course completely overlap at the interaction point. The precise measurement of all parameters which enter into the luminosity determination cannot be performed with the required accuracy. Since, however, the luminosity is related to the interaction rate ϕ by Eq. (4.8), a process of well-known cross section σ can be used to fix the luminosity.

In e^+e^- colliders the well-understood QED process

$$e^+e^- \to e^+e^- \tag{4.10}$$

(*Bhabha scattering*, see Fig. 4.3), with a large cross section, can be precisely measured. Since this cross section is known theoretically with high precision, the e^+e^- luminosity can be accurately determined ($\delta L/L \ll\ 1\%$).

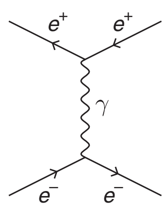

Fig. 4.3. Feynman diagram for Bhabha scattering in t-channel exchange.

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The luminosity determination in pp or $p\bar{p}$ colliders is more difficult. One could use the elastic scattering for calibration purposes or the W and/or Z production. In Z production one can rely on the decay $Z \to \mu^+\mu^-$. Since the cross section for Z production and the branching ratio into muon pairs are well known, the luminosity can be derived from the number of muon pairs recorded.

In $\gamma\gamma$ colliders the QED process

$$\gamma\gamma \to e^+e^- \tag{4.11}$$

could be the basis for the luminosity measurement. Unfortunately, this process is only sensitive to one spin configuration of the two photons so that further processes (like the radiative process $\gamma\gamma \to e^+e^-\gamma$) must be used to determine the total luminosity.

If energies beyond the reach of earthbound accelerators are required, one has to resort to *cosmic accelerators* [8–10]. Experiments with cosmic-ray particles are always fixed-target experiments. To obtain centre-of-mass energies beyond 10 TeV in pp collisions with cosmic-ray protons one has to use cosmic-ray energies of

$$E_{\text{lab}} \geq \frac{s}{2m_p} \approx 50\,\text{PeV}(= 5 \cdot 10^{16}\,\text{eV}) \ . \tag{4.12}$$

Since one has no command over the cosmic-ray beam, one must live with the low intensity of cosmic-ray particles at the high energies.

4.1 Problems

4.1 At the Large Hadron Collider the centre-of-mass energy of the two head-on colliding protons is 14 TeV. How does this compare to a cosmic-ray experiment where an energetic proton collides with a proton at rest?

4.2 A betatron essentially works like a transformer. The current in an evacuated beam pipe acts as a secondary winding. The primary coil induces a voltage

$$U = \int \vec{E} \cdot \mathrm{d}\vec{s} = |\vec{E}| \cdot 2\pi R = -\frac{\mathrm{d}\phi}{\mathrm{d}t} = -\pi R^2 \frac{\mathrm{d}B}{\mathrm{d}t} \ .$$

While the induction increases by $\mathrm{d}B$, the accelerated electron gains an energy

$$\mathrm{d}E = e\,\mathrm{d}U = e|\vec{E}|\,\mathrm{d}s = e \cdot \frac{1}{2} R \frac{\mathrm{d}B}{\mathrm{d}t}\,\mathrm{d}s = e\frac{R}{2} v\,\mathrm{d}B \ , \quad v = \frac{\mathrm{d}s}{\mathrm{d}t} \ . \tag{4.13}$$

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If the electron could be forced to stay on a closed orbit, it would gain the energy

$$E = e\frac{R}{2}\int_0^B v\,\mathrm{d}B \ .$$

To achieve this a guiding field which compensates the centrifugal force is required. Work out the relative strength of this steering field in relation to the accelerating time-dependent field B.

4.3 A possible uncontrolled beam loss in a proton storage ring might cause severe damage. Assume that a beam of 7 TeV protons ($N_p = 2\cdot 10^{13}$) is dumped into a stainless-steel pipe of 3 mm thickness over a length of 3 m. The lateral width of the beam is assumed to be 1 mm. The 3 mm thick beam pipe absorbs about 0.3% of the proton energy. What happens to the beam pipe hit by the proton beam?

4.4 The LEP dipoles allow a maximum field of $B = 0.135\,\mathrm{T}$. They cover about two thirds of the 27 km long storage ring. What is the maximum electron energy that can be stored in LEP?

For LHC 10 T magnets are foreseen. What would be the maximum storable proton momentum?

4.5 Quadrupoles are used in accelerators for beam focussing. Let z be the direction of the beam. If ℓ is the length of the bending magnet, the bending angle α is

$$\alpha = \frac{\ell}{\rho} = \frac{e\,B_y}{p}\cdot\ell \ .$$

To achieve a focussing effect, this bending angle must be proportional to the beam excursion in x:

$$\alpha \propto x \ \Rightarrow \ B_y\cdot\ell \propto x \ ;$$

for symmetry reasons: $B_x\cdot\ell \propto y$.

Which magnetic potential fulfils these conditions, and what is the shape of the surface of the quadrupole magnet?

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