

Introduction

1.1 Motivation and overview

The reasons for studying accelerator physics fall into two basic categories: first, to design, build, and improve real accelerators for use as tools, and second, to study the dynamics of particle motion in a non-linear system.

Some of the tools provide energy to process matter such as electron beam welding, x-ray lithography, cancer therapy, preparation of radioisotopes for medicine, food sterilization and Star Wars. Other accelerators are used as microscopes to study matter and fundamental interactions of nature. Examples of these are cathode ray tubes, electron microscopes, accelerators for studying nuclear and high energy physics.

A particle accelerator can also be used as an analog computer to test models of non-linear dynamics. The two mechanical systems in the physical universe, that are closest to being linear systems, are accelerators, and the solar system. Of the two, accelerators provide the more linear case. They can be observed over many more cycles, since the particles in an accelerator usually travel much faster than planets, and their orbits are much smaller than planets.

In this book we only consider accelerators that accelerate microscopic particles such as electrons, protons, and ions under the influence of electromagnetic fields. This influence can be divided into two effects: longitudinal acceleration due to electric fields along the direction of motion of the particle, and transverse bending of the trajectory due to transverse electric and magnetic fields. The motion of charged particles is determined by the relativistic extensions to Newton's laws and the Lorentz force,

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}). \quad (1.1)$$

For particles with spin, there is another force

$$\vec{F} = \nabla(\vec{\mu} \cdot \vec{B}), \quad (1.2)$$

where $\vec{\mu}$ is the magnetic moment of the particle. This spin force is much smaller than the Lorentz force for a charged particle, but for a neutral particle of low momentum, it can be a useful effect.

Particle accelerators for the most part are divided into linear accelerators that accelerate the beam in a single pass, and circular accelerators that recirculate the beam through the accelerating voltage many times. Some examples of the linear type are the Van de Graaff generator, the Cockcroft-Walton cascade generator, the radio frequency quadrupole (RFQ), and the drift tube linac (DTL). The circular accelerators include cyclotrons, synchrocyclotrons, betatrons, microtrons, and synchrotrons.

Some simple parameters of importance to the user are: input power, the type of particle accelerated, the average beam energy, the distribution of energy of the particles in the beam, the angular divergence, intensity, duty factor, repetition rate, background rates, the polarization of the beam and target, and the cost. These are fairly obvious concepts; however, some of the definitions used for intensity deserve a little clarification.

For example let us consider the requirements for a high energy physics experiment. The experiment is trying to measure some esoteric process like¹

$$e^+ + e^- \rightarrow \Upsilon(4s) \rightarrow B^+ + B^-. \quad (1.3)$$

This type of experiment would probably be done with colliding electron and positron beams in a storage ring. This type of reaction has a certain production cross section, which when multiplied by something called the luminosity gives the rate of production of the B mesons. The usual backhanded definition of luminosity is: the number, that when multiplied by the cross section yields the interaction rate. The units for cross section are [cm^2] or sometimes the [barn = 10^{-24}cm^2]. The instantaneous luminosity (see Appendix B) has units of [$\text{cm}^{-2} \cdot \text{s}^{-1}$], and is proportional to the overlap integral of the densities of the two beams,

$$\mathcal{L} = |\vec{v}_+ - \vec{v}_-| f_0 \iiint \rho_+(\vec{x} - \vec{v}_+ t, t) \rho_-(\vec{x} - \vec{v}_- t, t) dx dy dz dt, \quad (1.4)$$

where v_+ and v_- are the velocities of the beams in the lab, f_0 is the frequency of beam crossings, and the integrations are carried out for a single crossing of bunches. (Note that for extremely relativistic head-on collisions in the center of mass, the factor $|\vec{v}_+ - \vec{v}_-| = 2c$. Simply put, it takes half as long for two beams to pass each other if they are moving towards each other than if one is stationary.) The densities, ρ_- and ρ_+ are the densities of the respective electron and positron bunches, and will vary in z with the shape of the beam envelope. The total number of such interactions in an experiment is given by the cross section times the integrated

luminosity, which is defined as the instantaneous luminosity integrated over the total time of the experiment. If more there is more than one bunch per beam, the number of bunch crossings at a given interaction point (i. e., for a single experiment) is increased by the number of bunches, N_b .

Of course for a useful number, we must account for any dead time of the experimental apparatus. In order to identify the B mesons in this experiment, the detector must identify the tracks of the particles from the decays of the B mesons. The detector takes a certain amount of time to accumulate and log the data, producing a period of time in which the detector is unable to identify a new event. This is called the dead time of the detector.

This type of event produces many daughter particles, and if there are two simultaneous events, the data is usually too confused to be useful. Because of this confusion, it is useless to have the average number of interactions per beam crossing greater than some value (usually one or less for most experiments.)

For an experiment with a single beam incident on a fixed target, the intensity is traditionally quoted as the number of beam particles hitting the target per second, rather than as a luminosity.

Two other terms used for defining intensities are used with synchrotron light sources: brightness and brilliance. Both are proportional to the number of photons hitting the target per second, but they have the added feature of being inversely proportional to the band width, or energy spread of the photon beam. Brightness is defined as the number dn , of photons per time interval dt , passing through a solid angle $d\Omega$, and divided by 0.1% of the bandwidth $d\lambda/\lambda$,

$$\Phi_{\Omega} = 1000 \frac{d^4 n}{dt d\Omega (d\lambda/\lambda)}. \quad (1.5)$$

Brilliance is defined as the brightness per area, s , of the source,

$$B = \frac{d\Phi_{\Omega}}{ds}. \quad (1.6)$$

In the rest of this chapter we review some basic concepts and briefly discuss a few of the early types of particle accelerators, which illustrate the different techniques used to accelerate charged particles.

1.2 Direct-voltage accelerators

The simplest type of elementary particle accelerator is a source of electrons or ions, and a pair of electrodes, activated by a potential drop ΔV , as shown in Fig. 1.1.