IOP Concise Physics

A Tour of the Subatomic Zoo

A guide to particle physics

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Chapter 7

Particle accelerators

Particle accelerators are a basic tool of high-energy physics. The majority of the discoveries and theories we have discussed would not have been possible without accelerators and the detectors designed to go with them. In this chapter we will learn about the different types of accelerators:

- linear
- linear collider
- fixed target
- colliders.

7.1 Acceleration of charged particles

If a charged particle passes through a region where there is an electric field, it will experience a force, as indicated in figure 7.1. Positively charged particles, like protons, are accelerated in the direction of the electric field: their speed will increase in that direction. Negatively charged particles, like electrons, will be accelerated in the direction opposite to the direction of the electric field, and their speed will increase in that opposite direction. This increase in the speed of a particle results in

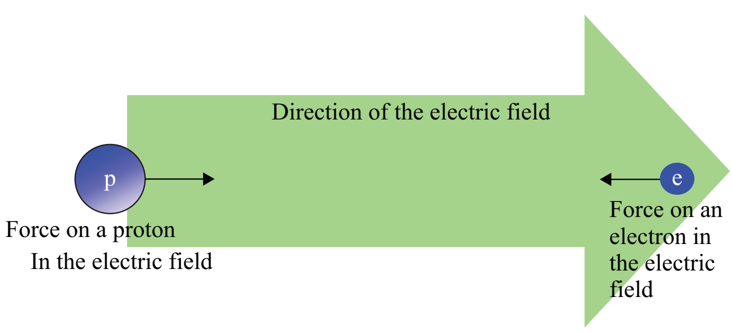

Figure 7.1. Acceleration of charged particles.

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an increase in the energy (kinetic) of the particle, which is the basic goal of a particle accelerator: to increase the energy of a particle. This increase in energy allows one to study more interesting particle reactions.

> *First, if we want really extensive reactions to occur, we need to supply a lot of energy to the reaction system. The best way to do this is for us to achieve high speeds. We can't accelerate to the necessary speeds on our own, so the people place us in electric fields. These make us speed up really fast (those of us with a charged nature anyway).*
>
> *Christina Lomasney*

The majority of particles that are accelerated in high-energy physics are antiprotons, protons, electrons, and positrons ($\bar{p}$, p, e^+, e^-), for the simple reason that they are stable and have charge. Technically, each one can be used in any of the four types of accelerators, but not all cases are practical.

7.2 Linear accelerators

A linear accelerator (linac) is the simplest type to understand. Particles are injected at one end, are accelerated by electric fields, and come out the other end with a higher energy (as can be seen in figure 7.2). The longer the linac, the higher the energy of the exiting particle. Many important experiments were done at SLAC (the Stanford Linear Accelerator Center) in California. The SLAC linac is two miles long and can accelerate electrons or positrons to 50 GeV (giga electron volts). GeVs are standard units for mass or energy in high-energy physics. To put these units in perspective, 1 GeV is approximately equal to the mass energy of a proton (from Einstein's $E = mc^2$). Electrons emerging from the linac have speeds very close to the speed of light! Protons and antiprotons can also be accelerated in linear accelerators; however, since they are more massive (close to 2000 times the electron), the acceleration process is more complicated and expensive.

Figure 7.2. Linear accelerator.

7.3 Linear colliders

A new machine began operation at SLAC in 1989 called the Stanford Linear Collider (SLC). The existing linear accelerator was used to accelerate a beam of positrons and a beam of electrons side by side. Magnetic fields were then used to bend the particles along arcs in a newly constructed section to an area where they could collide (see figure 7.3). In April 1989, the first 100 GeV *collisions* of electrons and positrons were recorded. These collisions were studied, and physicists were able to measure the mass of the Z particle (one of the carriers of the weak force) more accurately. This kind of machine is a single-pass collider; that is, the particle beams have one chance to collide, and then you begin again with new beams. For more up-to-date information on all the science going on at SLAC you can go to https://www6.slac.stanford.edu/files/SLAC_Stanford_report_2016_final.pdf.

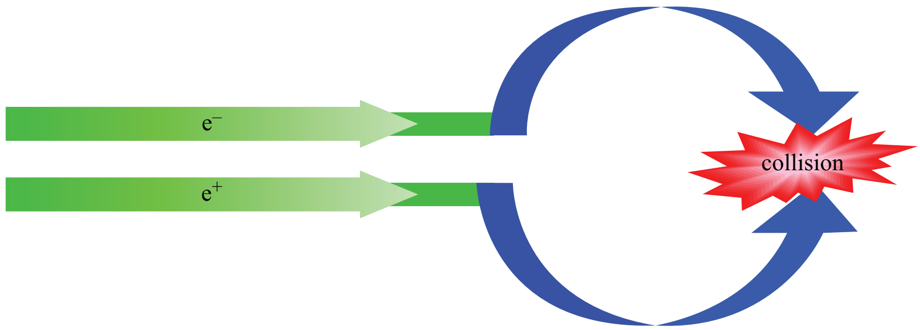

Figure 7.3. Linear collider.

7.4 Synchrotrons

A synchrotron accelerates particles using electric fields over and over in a circular path. Magnetic fields are used to bend the particle trajectories and keep them moving in a circle. Proton synchrotrons are more practical to achieve higher energies than electron synchrotrons. When electrons or positrons are accelerated in a synchrotron, they lose so much energy rounding the curves that a large part of the accelerator is taken up with making up this energy loss, rather than accelerating the particles to a higher energy. Beyond an energy of 10 or 20 GeV, a linear accelerator is more economical for accelerating electrons or positrons. When a charged particle is accelerated in a circular path, the particle will radiate (lose) energy. The amount of energy lost depends on how sharp the bend of the circular path is and how massive the particle is. Lighter particles will lose more energy, and this loss will therefore be a much greater problem for electrons (or positrons) than protons (or antiprotons). It will also be less of a problem if the accelerator has a very large circumference. Antiprotons can be accelerated this way, but the difficult part there is making and storing the antiprotons in the first place.

Figure 7.4 shows a simple model of a proton synchrotron. These are also called fixed-target machines, because the beam of moving particles, once extracted, strikes a stationary target. The operation of such an accelerator can be thought of as having three stages:

- protons are injected into the ring by a linac
- they circulate until the desired energy is reached
- they are extracted as a beam (or beams) heading toward targets or detectors.

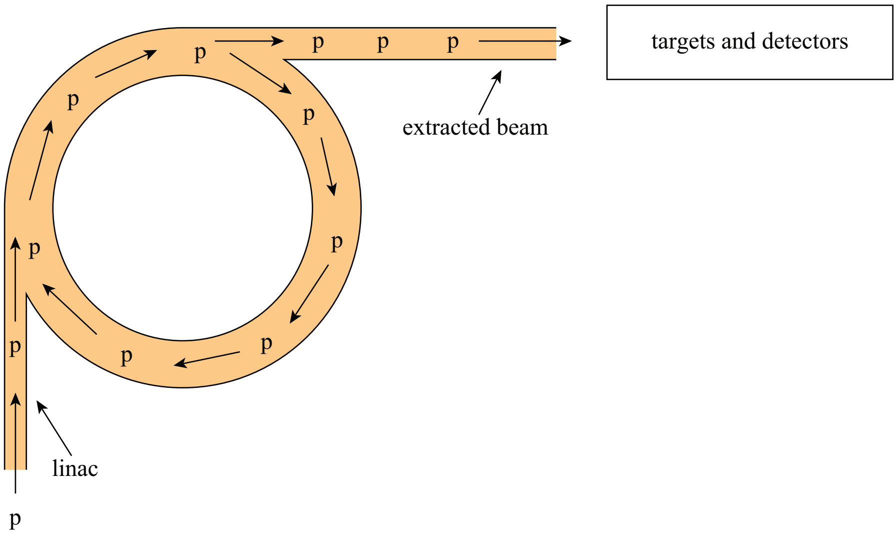

Figure 7.4. Proton synchrotron.

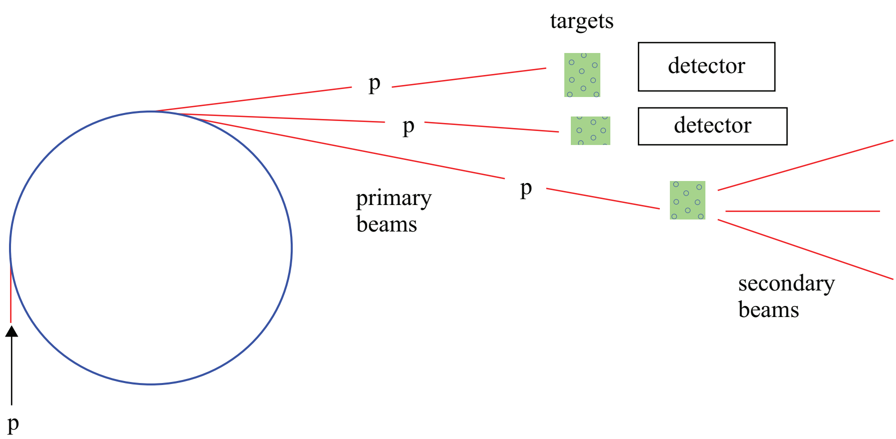

Figure 7.5. Secondary beams.

One very useful feature of a fixed-target machine is its ability to make secondary beams, which can be seen schematically in figure 7.5. When the primary proton beam strikes the stationary target, many different types of particles are produced. The particles shown in figure 7.6 are just examples, and there are many other possibilities. If a magnet is placed in the path of the particles, the positive ones will bend one way, the negative ones will bend the other way, and the neutral ones will pass straight through. In this manner one can separate beams with different charges. Other techniques can be used to further separate the particles and provide a uniform particle beam. There are proton synchrotrons at Brookhaven National Lab, Fermilab, and CERN, to name a few (see table 7.2).

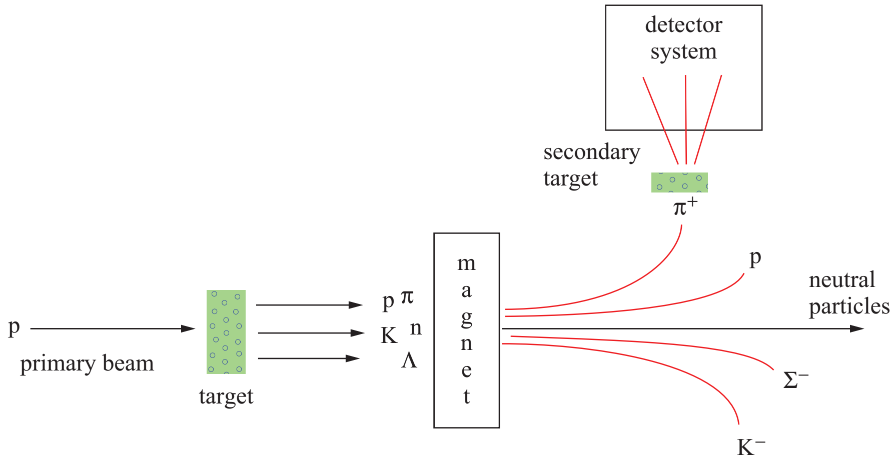

Figure 7.6. Secondary beams (details).

7.5 Colliders

The other kind of circular accelerator used in high-energy physics research is the collider. In this type of machine, two beams of particles are accelerated in opposite directions. When the proper energy is achieved, the beams are allowed to cross and collide (see figure 7.7). Currently the accelerators capable of the highest energy processes are colliders (e^+e^-, pp, e^-p, or $p\bar{p}$). The largest electron–positron collider in the world is called LEP (for Large Electron Positron collider), and it began operating in the summer of 1989 in Geneva, Switzerland. The experiments there have already been successful in placing strong limits on the number of neutrinos and determining the Z mass more precisely. This will probably be the last electron–positron circular collider ever built, because to increase the energy substantially would require a much larger machine, and LEP already has a circumference of 27 kilometers. It may be

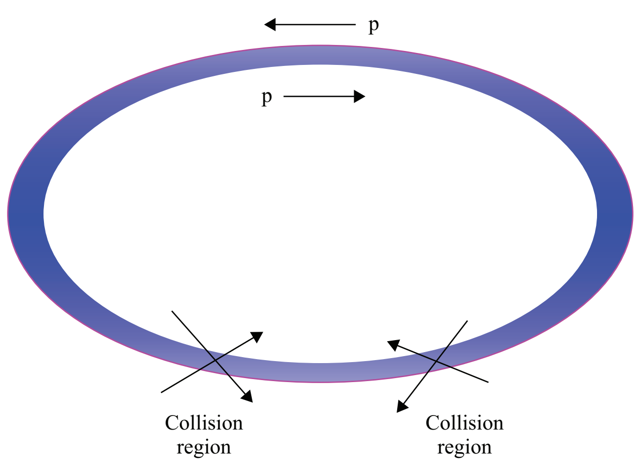

Figure 7.7. Collider.

possible to get higher energy electron–positron collisions with machines like the SLC or two linear accelerators firing particle beams head on. Much of the interesting physics is expected to come from experiments done at the LHC (Large Hadron Collider at CERN in Geneva), which began operation in 2008. The table at the end of this chapter gives information on some accelerators of the past, present, and future.

One of the big advantages of a collider is the amount of energy available from the collisions. Imagine a car moving at 30 miles per hour hitting a stationary car and the damage that might be done. Now imagine two cars, each moving at 30 miles per hour, colliding head on. The damage done is most definitely greater. The same principles can be applied to fixed-target and collider accelerators. As can be seen in the table below, you get much more energy for producing new particles in a collider. Furthermore, doubling the beam energy in a collider doubles the available energy, which is not the case for a fixed-target machine. In table 7.1, energies are quoted in GeV's, where 1 GeV is approximately equal to the mass of a proton.

Table 7.1. Collider versus fixed target.

Type of accelerator	Energy of incoming particle (s)	Energy available for production of new particles
Fixed target	500 GeV protons	31 GeV
Collider	500 GeV protons	1000 GeV
Fixed target	1000 GeV protons	44 GeV
Collider	1000 GeV protons	2000 GeV

'Look out! We're being collected!' The helium atoms scattered to avoid the physicists. Lucy the Proton stayed still, excited and expectant. Today was her lucky day. She was pretty sure that she was going to be put into a particle accelerator. The ride to the accelerator wasn't bad. The accelerator turned out to be vast and menacing, a large coil of a snake. There was an ominous detection center of some sort, but Lucy could not quite see it. She cried out as she was separated from her atom and put into a large box. It was there that she met Andrew, another proton. 'Are you ready to smash?' he asked. 'I heard that they smash us into antiprotons. Imagine that.' 'Yes I heard', Lucy replied. 'You know, most protons would be afraid of antimatter, but for some reason, I'm not. Oh, wow, what if we turn into top quarks?…'

Alyssa Babcock

Table 7.2. Some past, present, and future accelerators.

Name	Type	Energy	Location	Years
Cosmotron	p synchrotron	3 GeV	Brookhaven, NY	1952–67
AGS	p synchrotron	28 GeV	Brookhaven, NY	1961–Present
SLAC	e^- linac	50 GeV	Stanford, California	1961–98
Fermilab	p synchrotron	400 GeV	Batavia, Illinois	1972–95
CERN S p, $\bar{p}$ S	p, $\bar{p}$ collider	900 GeV	Geneva, Switzerland	1981–90
Tevatron	p, $\bar{p}$ collider	2,000 GeV	Batavia, Illinois	1987–2011
SLC	e^-, e^+ linear collider	100 GeV	Stanford, California	1989–98
LEP	e^-, e^+ collider	180 GeV	Geneva, Switzerland	1989–2000
HERA	e^-, p collider	30 GeV (e^-) 820 GeV (p)	Hamburg, Germany	1992–2007
DAΦNE	e^-, e^+ collider	1 GeV	Frascati, Italy	1997–Present
LHC	p, p collider	14,000 GeV	Geneva, Switzerland	2008–Present
RHIC	Gold collider	10 GeV	Brookhaven, NY	2000–Present
KEK	e, p collider	8.0 GeV	Tsukuba, Japan	1997–Present
BEPC II	e, p collider	3.7 GeV	Beijing, China	2008–Present
NSLS	e synchrotron	3.0 GeV	Brookhaven, NY	1982–2014

Particle accelerators: https://www.youtube.com/watch?v=G6mmIzRz_f8

Summary

In this chapter we learned about four types of accelerators.

- Linear accelerator
  - particles are injected at one end and emerge from the other end with a higher energy
  - disadvantage: they must be very long to achieve high energies
  - example: SLAC linac in California.
- Linear collider
  - an adaptation on a linear accelerator that allows beams accelerated side by side to collide
  - advantage: not as much energy is lost for electrons and positrons as in circular machines
  - disadvantage: single chance for collision, therefore beams must be highly focused
  - example: SLC in California.
- Fixed target

  - electric and magnetic fields are used to accelerate particles (typically protons) around a circular path over and over. When the desired energy is attained, the particles are ejected from the accelerator as a beam
  - advantage: secondary beams are possible
  - example: Brookhaven Alternating Gradient Synchrotron (AGS) in Long Island, New York.
- Collider
  - two beams of particles are accelerated in opposite directions and, when the proper energy is achieved, the beams are allowed to cross and collide. Currently the accelerators that are capable of the highest energy processes are colliders.
  - advantage: high energies available to create new particles.
  - example: Large Hadron Collider (LHC) in Geneva.

Self-test 7

For multiple choice, check all that apply.

1. An electric field can be used to accelerate
   a. protons.
   b. neutrons.
   c. positrons.
   d. neutrinos.
2. If a magnetic field bends electrons to the left it will bend
   a. protons to the right.
   b. neutrons to the left.
   c. positrons to the left.
   d. neutrinos either right or left.
3. A linear accelerator
   a. can only accelerate protons.
   b. must be very long to get high energies.
   c. uses magnetic fields to bend particles.
4. A collider accelerator
   a. uses electric and magnetic fields.
   b. can only accelerate protons.
   c. can accelerate antimatter.
5. One advantage of a fixed-target machine is
   a. it uses no electric fields.
   b. it can produce secondary beams.
   c. it can accelerate antimatter.

Answers to self-test 7

1. An electric field can be used to accelerate
   a. protons. ×
   b. neutrons.
   c. positrons. ×
   d. neutrinos.
2. If a magnetic field bends electrons to the left it will bend
   a. protons to the right. ×
   b. neutrons to the left.
   c. positrons to the left.
   d. neutrinos either right or left.
3. A linear accelerator
   a. can only accelerate protons.
   b. must be very long to get high energies. ×
   c. uses magnetic fields to bend particles.
4. A collider accelerator
   a. uses electric and magnetic fields. ×
   b. can only accelerate protons.
   c. can accelerate antimatter. ×
5. One advantage of a fixed-target machine is
   a. it uses no electric fields.
   b. it can produce secondary beams. ×
   c. it can accelerate antimatter.