start from the source and are accelerated to paths of larger and larger radii. But this is only true at nonrelativistic energies. At higher speeds, the momentum (Eq. 26–4) is $p = m_0 v/\sqrt{1 - v^2/c^2}$, so m in Eq. 32–2 has to be replaced by γm_0 and the cyclotron frequency f (Eq. 32–2) depends on speed v. To keep the particles in synch, machines called **synchrocyclotrons** reduce the frequency in time, in parallel with the mass increase, as a packet of charged particles increases in speed and mass at larger orbits.

Synchrotron

Synchrotron

Another way to accelerate relativistic particles is to increase the magnetic field B in time so as to keep f (Eq. 32–2) constant as the particles speed up. Such devices are called **synchrotrons**, and today they can be enormous. At the European Center for Nuclear Research (CERN) in Geneva, Switzerland, the new (2007) Large Hadron Collider (LHC) will be 4.3 km in radius and accelerate protons to 7 TeV. The *Tevatron* accelerator at Fermilab (the Fermi National Accelerator Laboratory) at Batavia, Illinois, has a radius of 1.0 km. The Tevatron uses superconducting magnets to accelerate protons to about $1000\ \text{GeV} = 1\ \text{TeV}$ (hence its name); $1\ \text{TeV} = 10^{12}\ \text{eV}$. These large synchrotrons use a narrow ring of magnets (see Fig. 32–3) with each magnet placed at the same radius from the center of the circle. The magnets are interrupted by gaps where high voltage accelerates the particles; another way to describe the acceleration is to say the particles "surf" on a traveling electromagnetic wave within radiofrequency (RF) cavities.

FIGURE 32–3 (a) Aerial view of Fermilab at Batavia, Illinois; the main accelerator is a circular ring 1.0 km in radius. (b) The interior of the tunnel of the main accelerator at Fermilab. The upper (rectangular-shaped) ring of magnets is for the older 500-GeV accelerator. Below it is the ring of superconducting magnets for the 1-TeV Tevatron.

(a) (b)

Once charged particles are injected, they must move in a circle of constant radius. This is accomplished by giving them considerable energy initially in a smaller accelerator (the injector), and then slowly increasing the magnetic field as they speed up in the large synchrotron.

One problem of any accelerator is that accelerating electric charges radiate electromagnetic energy (see Chapter 22). Since ions or electrons are accelerated in an accelerator, we can expect considerable energy to be lost by radiation. The effect increases with energy and is especially important in circular machines where centripetal acceleration is present, such as synchrotrons, and hence is called **synchrotron radiation**. Synchrotron radiation can be useful, however. Intense beams of photons are sometimes needed, and they are usually obtained from an electron synchrotron.

Synchrotron radiation