Ernest Courant, M. Stanley Livingston, and Hartland Snyder (left to right), who conceived the idea of strong focussing. (Courtesy Brookhaven National Laboratory)

Lawrence's cyclotrons obeyed an approximately cubic relationship between size or cost and the momentum of the accelerated particle. The magnet's radius grew linearly with the momentum, and the magnet gap also had to increase accordingly to provide enough clearance for the higher radio-frequency voltages required to keep particles and the voltage crest synchronized. All this changed in 1945 with the invention of phase stability by Edwin McMillan and Vladimir Vexler. Their independent work showed that only moderate radio-frequency voltages are required in circular machines because all the particles can be "locked" in synchronism with the accelerating fields.

Then came the 1952 invention of strong focusing, again independently by Nicholas Christophilos and by Ernest Courant, Livingston, and Hartland Snyder (see photograph on the right). Conventional wisdom says that a magnetic lens to focus particles both horizontally and vertically cannot be constructed— in contrast to optical lenses, which can. But the principle of strong focusing showed that, while a magnetic lens indeed focuses in one plane and defocuses in the orthogonal plane, if two such lenses are separated along the beam path, then their net effect is to focus in both planes simultaneously. This breakthrough made it possible to squeeze beams in circular (and also linear!) accelerators to much tighter dimensions, thus reducing magnetic field volumes and therefore costs.

Because the basic linear scaling laws apply to linear machines for both electrons and protons, prominent physicists predicted that all future accelerators would eventually be linear. But the question remained, "Where is the crossover in costs between circular and linear machines?" New inventions, particularly strong focusing, raised the predicted crossover to much higher energy. Moreover, strong focusing also made the scaling law for high energy proton synchrotrons almost linear. The transverse dimensions of the beam aperture do not need to grow very much with energy; thus the cost of large circular proton colliders grows roughly linearly with energy.

While the scaling laws for proton machines are not affected significantly by radiation losses (although such losses are by no means negligible for the largest proton colliders), they become the dominant factor for circular electron machines. The radiation energy loss per turn of a circulating electron varies as the fourth power of the energy divided by the machine radius. It is also inversely proportional to the mass of the circulating particle, which tells you why electrons radiate much more profusely than protons. In an electron storage ring, certain costs are roughly proportional to its radius while others are proportional to the radiation loss, which must be compensated by building large and expensive radio-frequency amplifiers. As the energy grows, it therefore becomes necessary to increase the radius. The total cost of the radio-frequency systems and the ring itself will be roughly minimized if the radius increases as the square of the energy.

Such a consideration therefore indicates that linear electron machines should eventually become less expensive than circular ones. But what is meant by the word "eventually?" The answer depends on the details. As designers of circular electron machines have been highly resourceful in reducing the costs of components, the crossover energy between circular and linear colliders has been increasing with time. But it appears likely that CERN's Large Electron-Positron collider (LEP), with its 28 kilometer circumference, will be the largest circular electron-positron collider ever built.

The only reasonable alternative is to have two linear accelerators, one with an electron beam and the other with a positron beam, aimed at one another—thereby bringing these beams into collision. This is the essential principle of a linear collider; much research and development has been dedicated to making such a machine a reality. SLAC pioneered this technology by cheating somewhat on the linear collider principle. Its linear collider SLC accelerates both electron and positron beams in the same two-mile accelerator; it brings these