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Positron-Electron Colliding Beam

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Positron-Electron Colliding Beams

Positron-electron colliding-beam machines are devices to produce a large collision rate between antimatter *(e+)* and matter *(e-)*. When antiparticles and particles collide, they can annihilate to produce a state of pure energy that can rematerialize into many different particles with very few restrictions on the kinds of particles that might be produced. When the antiparticle and particle are positron and electron, the intermediate pure energy state is particularly simple and well understood, its formation being described by the well tested theory of quantum electrodynamics. Most of the work with *e± colliding* beams has been the study of the properties and kinematic distributions of the particles produced when the intermediate pure-energy state rematerializes. The principal aim is to determine the interaction between these particles and to search for new particles that might exist with large rest masses. In the past years, experiments with *e±* colliding beams have uncovered many new particles, and taught us much about the interactions of these particles.

The basic design of the colliding-beam machine is dictated by the necessity of reaching a large enough interaction energy to produce the particles one wants to study. This interaction energy, or center-of-mass energy (E^*), for a particle of energy E_1, colliding with a particle of energy E_2, is given by

$$E^* = (4\, E_1\, E_2)^{1/2}.$$

For electrons or positrons, the rest-mass energies are the same and are about equal to ½ MeV (million electron volts), whereas the interaction energies of interest are many GeV (billion electron volts). For example, to reach an interaction energy of 92 GeV, to produce the Z^0 boson, would require a positron beam of about 5×10^6 GeV incident on an electron at rest. The world's largest electron accelerator is the 3-km-long linear accelerator at the Stanford Linear Accelerator Center (SLAC) in California, that can produce a beam of up to 50 GeV energy. Scaling up this accelerator to 5×10^6 GeV would require a machine about 3×10^5 km long. The obviously more practical solution to the problem of achieving large interaction energies is to make two equal-energy beams collide with each other; for our example, this would require beam energies of only 50 GeV each.

Two techniques are currently in use to produce large interaction rates in *e±* collisions—the *storage ring* and the *linear collider*. The storage ring is the older technology. Construction of the first such device, the Princeton-Stanford storage ring (500 MeV beam energy, 12 m circumference) began in 1958, whereas the largest such machine, the LEP ring at CERN (100 GeV energy, 27 km circumference) was completed in 1989 and operated through 2000.

The linear collider was conceived as a less costly alternative to the storage ring for very high energy machines. The first of these colliders, the SLC at Stanford (50 GeV per beam, 3 km in length) was completed in 1987 and operated through 1998; the next generation is presently being designed.

STORAGE RINGS

In an electron storage ring, beams of positrons and electrons circulate in opposite directions for periods of the order of hours between refills, colliding only at specially designed interaction regions. The basic processes that come into play in building up the necessary beam current are as follows.

A short bunch of either electrons or positrons is injected into the machine by a pulsed injection system of some kind. The injected particles are guided around a roughly circular closed orbit by a collection of bending and focusing magnets. Particles that are close to but not exactly on the closed orbit execute stable *betatron oscillations* around that orbit. The particles must travel in a very good vacuum so that collisions of the electrons or positrons with molecules of the residual gas in the vacuum system do not cause the particles to scatter or lose large amounts of energy and so be lost to the beam. Pressures of 10^{-8} to 10^{-9} Torr are typical.

As the particles are bent around the design orbit by the magnetic field, they lose energy by *synchrotron radiation.* This energy loss can be very large for high-energy colliders and is one of the problems that must be overcome in them. This energy loss is proportional to the fourth power of the beam energy divided by the radius of curvature in the bending magnets. The energy loss is made up by a radio-frequency (rf) accelerating system. The periodic rf acceleration field collects the particles into short bunches.

The interplay of the synchrotron-radiation processes, the bending and focusing fields, and the rf system results in a decay of all transverse and longitudinal components of a particle's momentum toward a final value with zero transverse momentum and a unique longitudinal momentum given by that corresponding to the ideal central orbit in the guide field. This time constant of this decay is the *radiation damping time.*

The radiation damping means that phase space is not conserved in the beam, and particles with large amplitudes of oscillation with respect to the design orbit will move toward that orbit. In particular, particles put into the ring by the injection system with large amplitudes will have those amplitudes shrink and thus will move away from the injection system. When they have moved far enough, another pulse of particles can be injected into the ring, and so forth. In this way, large circulating currents can be built up.

The synchrotron radiation is not a continuous process but a quantum-mechanical process, and the fluctuations in the synchrotron radiation tend to make the beam size increase. The interplay between radiation damping and the quantum fluctuations results eventually in a statistically stationary distribution of particle amplitudes. The distributions in longitudinal and transverse amplitudes are approximately Gaussian, and the standard deviations of these distributions give the *natural beam size.*

The interaction rate of $e+$ and $e-$ beams is measured by the *luminosity (L),* the interaction rate per unit cross section, given by

$$L = (N_B^2 / A) f_B,$$

where N_B is the number of particles in a bunch (assumed to be the same for the e+ and *e*− beams*),* A is the effective area of the bunch transverse to the direction of motion, and f_B is the collision frequency of the bunches in the machine. All of the present generation of *e*± *colliding-beam* machines use special focusing elements near the collision points to reduce A to as small a value as possible, and also use high power rf systems to allow large values of N_B.

There is, however, a limit to the particle density (N_B / A), referred to as the *tune shift limit,* beyond which the colliding beams become unstable and particles are lost from the ring. This limit comes from the very strong electromagnetic fields a particle in one beam feels as it passes through the other beam. These forces are equivalent to a nonlinear focusing lens whose strength is largest for a test particle near the center of the other beam and smallest for one far from the center. It has been found experimentally that the upper limit to the particle density corresponds to that which changes the number of betatron oscillations per turn by about 0.1 per collision region.

In addition, N_B itself is limited for a given machine by the available rf power to make up for synchrotron-radiation losses and by the very large peak currents in the beams which produce electromagnetic fields in the vacuum chamber that can interact back on the beam in a destructive fashion. The average circulating currents in early machines ranged from 50 mA to 0.5 A, with peak currents in the range of hundreds of amperes. Modern high luminosity factories operate with 1-3 amperes in each beam. The LEP2 machine required 3 GV of rf accelerating voltage to operate at its maximum energy.

Typical luminosities of early storage rings were 10^{31}-10^{32} $cm^{-2}s^{-1}$, whereas the physics cross sections of interest were 10^{-32}-10^{-35} giving event rates of 1.0 to 0.001 s^{-1}. The most recent generation of high luminosity factories now achieve luminosities close to 10^{34}.

The highest energy *e+e-* collider ever operated was the LEP machine at CERN, which in its second phase as LEP2 reached 104.4 GeV per beam before ceasing operation in 2000. Other colliders constructed included TRISTAN (28 GeV) at KEK in Japan; PEP (15 GeV) at Stanford and CESR (8 GeV) at Cornell in the United States; DORIS (5 GeV) at DESY in Germany; VEPP III (5 GeV) at Novosibirsk in Russia, and BEPC (2.5 GeV) at Beijing in China. The TRISTAN and PEP colliders have since been converted to asymmetric B-factories, renamed KEKB (8GeV e- on 3.5 GeV e+) and PEP-II (9 GeV e- on 3 GeV e+). The Adone machine at Frascati in Italy has been converted to Daphne, a Phi-factory (0.5 GeV). Recently CESR has been converted to CESR-C, a charm factory (1.5 GeV).

Synchrotron radiation from high-energy *e*± storage rings provides a very intense source of x rays in the region 0.1 to 50 keV. These x rays are used for studies in solid-state physics, chemistry, biology, and medicine. These studies have been so productive that dozens of special-purpose electron storage rings designed solely as sources of synchrotron radiation have been constructed around the world.

LINEAR COLLIDER

Because of the rapid increase of the energy loss through synchrotron radiation (proportional to E^4 / R), power demands of storage rings increase very rapidly with energy. It can be shown on quite general grounds that the minimum cost storage ring where circumference-dependent costs and rf-power-dependent costs are properly balanced has a scaling law that makes the size (and the cost) increase as the square of the beam energy. An electron storage ring 10 times the energy of LEP would have a hundred times the circumference (2700 km). Thus, storage rings much beyond the energy of LEP are not financially feasible.

The linear collider in its pure form consists of two linear accelerators firing beams of electrons and positrons at each other. Since there is no bending during the acceleration, there is no synchrotron radiation produced and the cost of these machines scales like the first power of the energy rather than the square. It is generally agreed in the accelerator physics community that for energy significantly beyond that of LEP, linear colliders will clearly be the less costly alternative.

The same equation [Eq. (2)] governs the luminosity of linear colliders and storage rings. The number of particles per bunch (N_B) tends to be about the same in the two kinds of machines, the collision frequency (f_B) is typically larger in storage rings, but because the beams do not recirculate, a linear collider can have a much larger *tune shift* than a storage ring and thus the particle density (N_B / A) can be much higher. Furthermore, because of the absence of quantum effects and synchrotron radiation in the acceleration process, the effective area (A) can be made much smaller in the linear collider. For example, the area of the beams at the collision point in the LEP storage ring was about a thousand times the area in the SLC.

There are three main components to a linear collider: the source, the main accelerator, and the final focus system. The source must produce beams that are capable of being focused to a very small size at the high-energy end. The figure of merit for the source is the invariant emittance (product of rms radius and transverse momentum of particles within the beam). The smaller the invariant emittance of the source, the smaller the beam spot that can be produced by the final focus system at the collision point. The sources for high-energy linear colliders all incorporate storage rings of 1-5 GeV energy that are designed to produce the required emittance through radiation damping (described above). The SLC damping rings produced beams with invariant emittance of about 3.5 by 0.5 x 10^{-5} m. The higher-energy machines now proposed will require emittances a factor of 10-500 times smaller, about 3.0 x 10^{-6} m horizontally and 1-2 x 10^{-8} m vertically.

The main accelerator must boost the beam to the required final energy without diluting the small emittance produced by the source. The SLC used a conventional linear accelerator. After many studies, it has been concluded that such exotic acceleration methods as lasers, plasmas, etc. are not practical for at least the foreseeable future and that the next generation of linear colliders will also use conventional linacs. The intensity of the bunches of particles required for the linear collider are very large (on the order of

10^{10} per bunch) and this brings in new problems. The most important of these are *wakefield* effects on the accelerated bunch itself. These wakefields are produced by interaction of the high intensity bunch with the accelerating structure which, in turn, interacts back on the bunch that produced the field and can severely affect the beam quality. The transverse wakefield can produce the worst effects. Since its intensity is proportional to the distance the beam lies off the axis of the accelerator, the beam must be held close to the symmetry axis of the linac, within 200 μm in the SLC and within 10 μm in future normal-conducting linacs that use beams with smaller invariant emittance.

The final focus system produces the tiny beam spots at the collision point that are required for high-luminosity operation. This is complicated because magnetic lenses used to focus beams have aberrations like those of glass lenses required to focus light beams. As with high-quality camera lenses, linear-collider final-focus systems combine many lenses of different properties to cancel aberrations and produce spots at the emittance limit, analogous to the diffraction limit in optical systems. The SLC produced a beam spot of about 1.4 μm horizontally by 0.7 μm vertically. Future machines will require much smaller beam sizes, as small as 1-2 nm in the vertical plane.

The SLC began operation for physics research in 1989 and ended operation in June, 1998. The SLC included all of the subsystems required for a future linear collider and provided invaluable experience with the diagnostics, controls, and tuning techniques needed to reliably deliver luminosity. The SLC experience provides the basis for any higher energy linear collider.

Today, the international community has reached a consensus that the next major facility for high energy physics should be a linear collider with a center-of-mass energy of 500 GeV, upgradeable to 1000 GeV. Groups in the United States, Japan and Europe have proposed designs for this collider based on either superconducting linacs (TESLA led by DESY in Germany) or X-band normal-conducting linacs (NLC led by SLAC in the US or GLC led by KEK in Japan). Both design concepts have demonstrated the necessary rf technology and are ready for approval. The R&D program has been international in scope with excellent information exchange and collaboration on many specific projects. The linear collider would be built as an international facility and construction could begin by 2010.