Fixed-Target Electron Accelerators

A tremendous amount of scientific insight has been garnered over the past half-century by using particle accelerators to study physical systems of sub-atomic dimensions. These giant instruments begin with particles at rest, then greatly increase their energy of motion, forming a narrow trajectory or <u>beam</u> of particles. In <u>fixed-target</u> accelerators, the particle beam impacts upon a stationary sample or <u>target</u> which contains or produces the sub-atomic system being studied. This is in distinction to <u>colliders</u>, where two beams are produced and are steered into each other so that their constituent particles can collide.

The acceleration process always relies on the particle being accelerated having an electric charge; however, both the details of producing the beam and the classes of scientific investigations possible vary widely with the specific type of particle being accelerated. This article discusses fixed-target accelerators which produce beams of electrons, the lightest charged particle.

As detailed below, the beam energy has a close connection with the size of the physical system studied. Here a useful unit of energy is a 'GeV,' i.e., a giga electron-volt. (One GeV, the energy an electron would have if accelerated through a billion volts, is equal to 1.6×10^{-10} joules.) To study systems on a distance scale much smaller than an atomic nucleus requires beam energies ranging from a few GeV up to hundreds of GeV and more.

A correct description of the accelerated electrons' motion requires Einstein's theory of special relativity, because their speed is close to the speed of light. For example, an electron with only 0.01 GeV of energy is already traveling at 99.9 percent the speed of light. This simplifies the acceleration scheme because no matter what energy the beam has at a given stage of acceleration, the speed of its particles is nearly constant.

All high-energy accelerators use a rapidly-alternating high voltage to accelerate charged particles. (Constant high voltages, which can also accelerate particles, are not practical for particle acceleration above 0.1 GeV because of material property limitations.) The geometry of the accelerating structure is periodic, and the arrival times of the particles are synchronized so that as they are transported along they feel a 'push' where the accelerating electric field is large and pointing in the direction of motion, but no 'pull' where the electric field switches back and becomes small. One consequence is that the particles must be accelerated in separate groups or bunches. If the beam bunches arrive at the target separated by a short time interval (such as a few nanoseconds), then the beam is considered to be 'continuous' compared to the overall detector response, which is usually much slower. The structures most commonly used to provide the accelerating voltage are electromagnetically resonating cavities which allow very high voltages to be developed at a particular frequency. The alternating high voltage is conventionally referred to as RF from the historical use of 'radio frequencies' for this purpose. Linear accelerators, or linacs, consist of an arrangement of numerous resonating cavities in a line, through which the beam passes. (An alternative type of circular accelerator, the synchrotron, is not as well-suited for high energy electrons unless a very large circumference path is used. The beam particles emit a light called synchrotron radiation when they are forced into a curving path. This removes energy from the beam, decreasing its overall quality.) In RF cavities fabricated from ordinary electrical conductors such as copper, the large surface currents generated by the alternating high voltage create a significant amount of heat in the cavity material. An operational impact of this is that such high-field cavities have to be operated at a reduced duty factor, i.e., they are repeatedly switched off to cool after operating a short time; duty factors of one percent or less are common, that is, the cavities are cooling off ninety-nine percent of the time, during which no beam is accelerated. A major recent development in accelerator science has been the successful implementation of RF cavities fabricated from superconducting materials, in which the electrical resistance is greatly reduced. Although incurring the need for a helium cryogenic facility for cooling the cavities, this development has provided not only a means of achieving significant electrical power savings, it has also resulted in greatly improved beam quality. Small beam diameters and divergences (together referred to as the beam emittance), an extremely well-defined beam momentum, and a duty factor of one hundred percent are noteworthy benefits of superconducting RF cavities. (An accelerator with a duty factor of one hundred percent is conventionally referred to as a cw machine, an abbreviation for 'continuous wave.') These new capabilities permit whole new classes of important measurements to be performed.

Fixed Target vs. Colliders

There are a number of differences between fixed-target accelerators and colliders. One advantage of fixed-target mode is that it provides great flexibility in the selection of targets, unlike colliders. For example, sophisticated cryogenic liquid targets which can absorb nearly a kilowatt of power without boiling have been developed at fixed-target facilities. Increasing the thickness of a given target (and consequently the reaction rate) is usually a simple matter, whereas for colliders the equivalent action of increasing the density of collisions is a complex undertaking. This is because highly focused colliding beams tend to become less dense when they overlap, due to very strong electromagnetic forces. The 'density of collisions' is quantified by the luminosity, which for fixed-target accelerators is the product of the target thickness and the beam intensity. For a particular process, the reaction rate is simply proportional to the luminosity. The potential limitations on the luminosity achievable include both the beam current (current density for a collider) that the accelerator can produce, and the rate of outgoing particles which the particle detectors can accept without malfunctioning. Collider luminosities are typically several orders of magnitude smaller than those achieved in comparable fixed target accelerators.

The great advantage of colliders is that the amount of energy available for the reactions of interest is maximal. For colliding beams of equal momentum, all of the kinetic energy of the beams is available for the interaction. By contrast, for fixed-target accelerators only a fraction of the kinetic energy of the beam is available, the rest constituting the energy of the center-of-mass. For example, for electron-proton scattering with a 4 GeV electron beam, approximately half of the kinetic energy is available for the reaction; at 50 GeV, only 17 percent is available, and the fraction continues to decrease as $E^{-1/2}$, where E is the electron beam energy. Since the costs of building an accelerator generally increase as the beam energy increases, a collider is clearly to be preferred at the highest beam energies for experiments which can tolerate their limitations. An additional feature of colliders is that the particles emerging from the collision tend to be spread out over a larger range of angles than in fixed target accelerators. This means that good detector acceptance (the range of particle angles and momenta to which the detector is sensitive) for particles scattered at small angles (relative to the initial beam direction) is more challenging to achieve in fixed target accelerators than in colliders.

Storage rings can be operated as a special category of fixed-target accelerators. In these devices the beam circulates in a ring-shaped path for an extended time, often minutes or hours. The beam is usually added, or injected, into the ring, from another accelerator. The targets can be very thin layers of solid material or gases which are located at a point on the ring; the same beam particles pass through these internal targets many times. In storage rings it is possible to make a high-purity internal gas target with high polarization, an important property related to the magnetic character of the target particle. External targets can also be used by extracting beam from the ring and transporting it to the target.

Scientific Topics

A wide variety of scientific topics can be addressed at fixed target electron accelerators. Of the three fundamental forces in the universe (the gravitational force, electroweak force, and strong force), the electrons which scatter from the targets are only capable of interacting via the electroweak force. This force is much weaker than the strong force at small distance scales, and therefore using the electron as a probe does not disturb the system under study as much as strongly interacting probes. A further advantage is that the electroweak interaction is well-understood. Studies with electron beams are complementary to those performed with other particle beam types (such as proton beams); some experimental quantities can only be efficiently accessed by one particular type of beam. Historically, the weakness of the electroweak force was a disadvantage because it meant that the rate at which interactions take place is much smaller than for strongly interacting beams, and therefore the experiments were of long duration and collected relatively few events. This disadvantage has been overcome by technological advances such as developing cw accelerators with high luminosities.

At subatomic distance scales, forces between particles are transmitted through the exchange of other particles. When the exchanged particle is transmitting the force, it is referred to as a virtual particle; it exists for a very brief time, and does not emerge from the interaction region. In the case of electron scattering, the dominant process is to exchange a single virtual photon. (Photons are the particles that make up visible light, as well as all other electromagnetic fields such as microwaves or X-rays.)

The characteristics of the virtual photon exchanged in an interaction are determined by measuring the characteristics of the electron scattered from the target. The energy of the scattered electron, and the angle at which it emerges (compared to the initial beam direction) yield the properties of the virtual photon. The energy transferred to the target can be determined, as can the distance scale at which the interaction takes place, which is determined by the virtual photon's momentum. (Accessing smaller distance scales requires larger momenta, which in turn require larger beam energies.) Using this information, many types of subatomic systems can be studied. For instance, basic properties of the proton and neutron can be determined, such as their distributions of charge and magnetization, which yield information on the nature and distribution of their constituent particles. Systems consisting of unstable particles that decay rapidly, such as highly excited protons or heavier mesons, can be produced and characterized as well.

A representative example of a line of scientific inquiry is the study of the structure of protons. Protons are thought to be made up of three particles called quarks, bound together by forces transmitted via the exchange of particles called gluons. These forces become extremely strong when the quarks are further apart, and are very weak when they are close together. A 'cloud' of short-lived virtual particles surrounds these stable quarks. The virtual particles include other quarks (called sea quarks) and gluons. Most of this complex picture of proton structure has been derived from fixed-target electron accelerators.

Other particles besides the electron can also be detected, and as might be expected, detecting two or more particles in coincidence yields significantly more information on the structure of subatomic systems. High-quality coincidence experiments place higher demands on the performance of the accelerator and detector, however. Important ingredients in coincidence experiments include high duty factor, high luminosity, and large acceptance detection. The high duty factor is essential for most coincidence experiments; all other things being equal, a given experiment would take one hundred times longer at an accelerator with a one percent duty factor than it would with a cw accelerator. The other two ingredients, luminosity and acceptance, can compensate for each other. For instance, designing a magnet-detector combination, or spectrometer, to measure a particle's momentum with very high precision will often require sacrificing detector acceptance. The lower acceptance can be compensated by increasing the luminosity, if permitted by the accelerator-detector combination.

Existing Facilities

Historically, there have been many fixed-target electron accelerators devoted to studies in nuclear and particle physics. Over time, there have been changes in both the scientific focus of the fields served by these accelerators and the state-of-the-art in accelerator technology. This has lead to the adaptation of many of the older machines to other purposes. For instance, some accelerators formerly used in particle physics as a primary accelerator now serve as injectors to larger accelerators, often for colliders with much higher energies.

Of the fixed-target electron accelerators devoted to nuclear or particle physics, the most recently constructed is the Continuous Electron Beam Accelerator Facility (CEBAF) at the Thomas Jefferson National Accelerator Facility in Virginia, U.S.A., a Department of Energy laboratory for nuclear physics. CEBAF consists of two superconducting linacs connected together by two magnetic arcs. The beam accelerated through the first linac is directed via an arc into the second linac, and further accelerated. The beam can be recirculated up to a total of five passes through each linac to achieve the maximum energy. Each time the beam emerges from the second linac, a fraction of it can be extracted and sent into an experimental area. The accelerator produces electron beams ranging from 0.4 GeV to 6 GeV in energy, with a beam current of up to two hundred microamperes. Very high beam polarization is available at high current, and beam can be delivered to multiple experimental areas so that up to three experiments can be performed simultaneously with three different energies, each with a cw beam. An excellent emittance produces tiny beam spot sizes of only a few hundred microns in diameter.

Accelerators with lower maximum beam energies include the MIT-Bates Linear Accelerator in Massachusetts, USA, and the MAMI facility in Mainz, Germany, both of which are capable of producing close to 1 GeV electron beams. The MAMI facility employs a three-stage specialized accelerator (called a microtron) to produce a cw beam of up to one hundred microamperes, with high polarization and a small beam spot size. The Bates facility consists of a pulsed, normal-conducting linac injecting into a storage ring with an internal target, along with external target capabilities. Another facility utilizing a storage ring at higher energies is ELSA in Bonn, Germany. By injecting high intensity current into a stretcher ring, a high duty factor is achieved at low beam currents for up to 3.5 GeV electrons.

High-energy electron and positron beams of up to nearly 30 GeV are used in combination with gas targets in the HERMES experiment, which uses the HERA storage ring at the DESY facility in Hamburg, Germany. These ultrapure gas targets include polarized hydrogen, deuterium, and helium-3, as well as other unpolarized gases.

The highest electron energies available for fixed-target experiments are found at Stanford Linear Accelerator Center (SLAC) in California, USA. This facility consists of a two-mile long, normal-conducting linac. Although the duty factor is typically quite low (e.g., 0.03 %), electrons of up to 50 GeV can be produced without beam quality degradation due to synchrotron radiation.

WORD COUNT: 2488 words.

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Each major accelerator referenced in this article has its own web site, often including excellent introductory-level content, and opportunities for further contact.

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Figure captions:

1. The layout of the Continuous Electron Beam Accelerator Facility at Jefferson Lab, showing the linacs, recirculating arcs, and experimental areas (labelled A, B, and C).
2. A conceptual cartoon showing an electron from the beam exchanging a virtual photon which interacts with a quark contained in a helium nucleus.
3. A photograph of a seven cell acceleration cavity fabricated from niobium, which is a superconductor at liquid helium temperatures. The cavity is approximately one meter in length.

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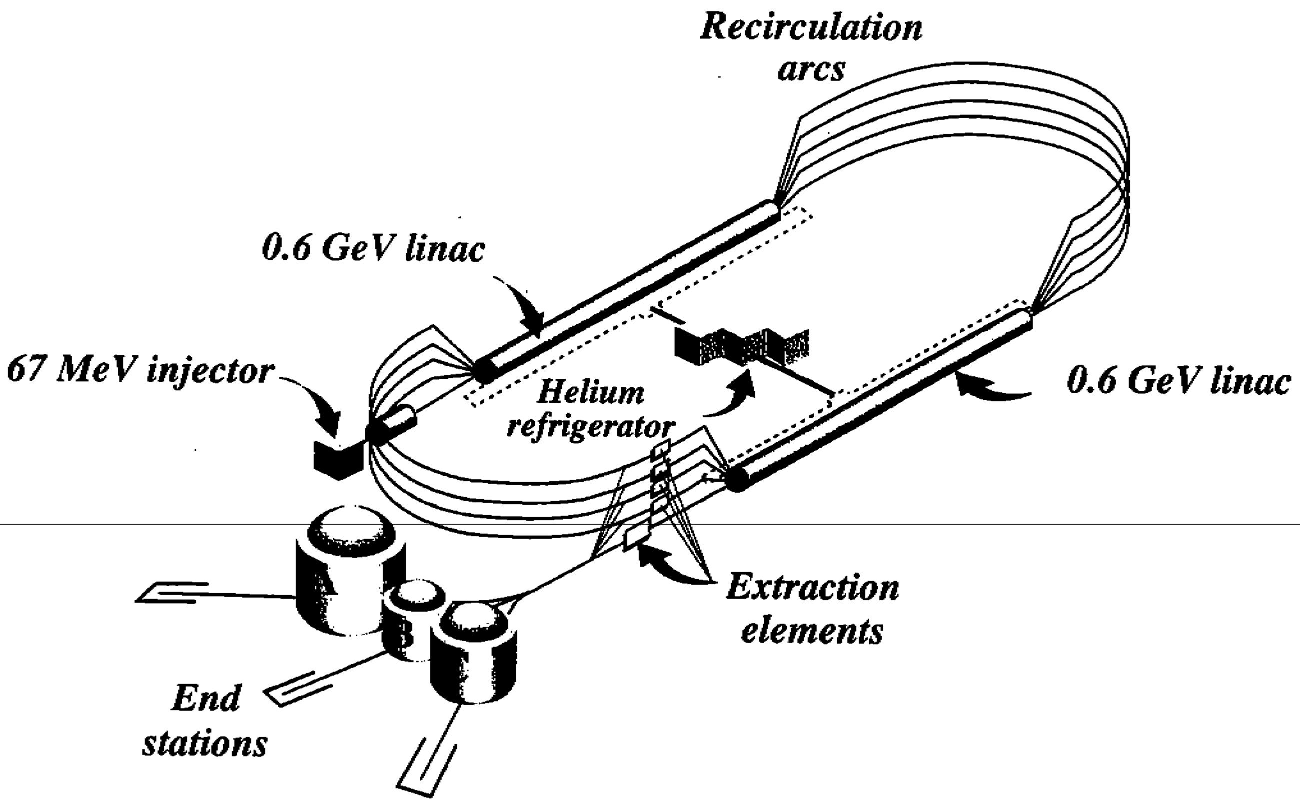
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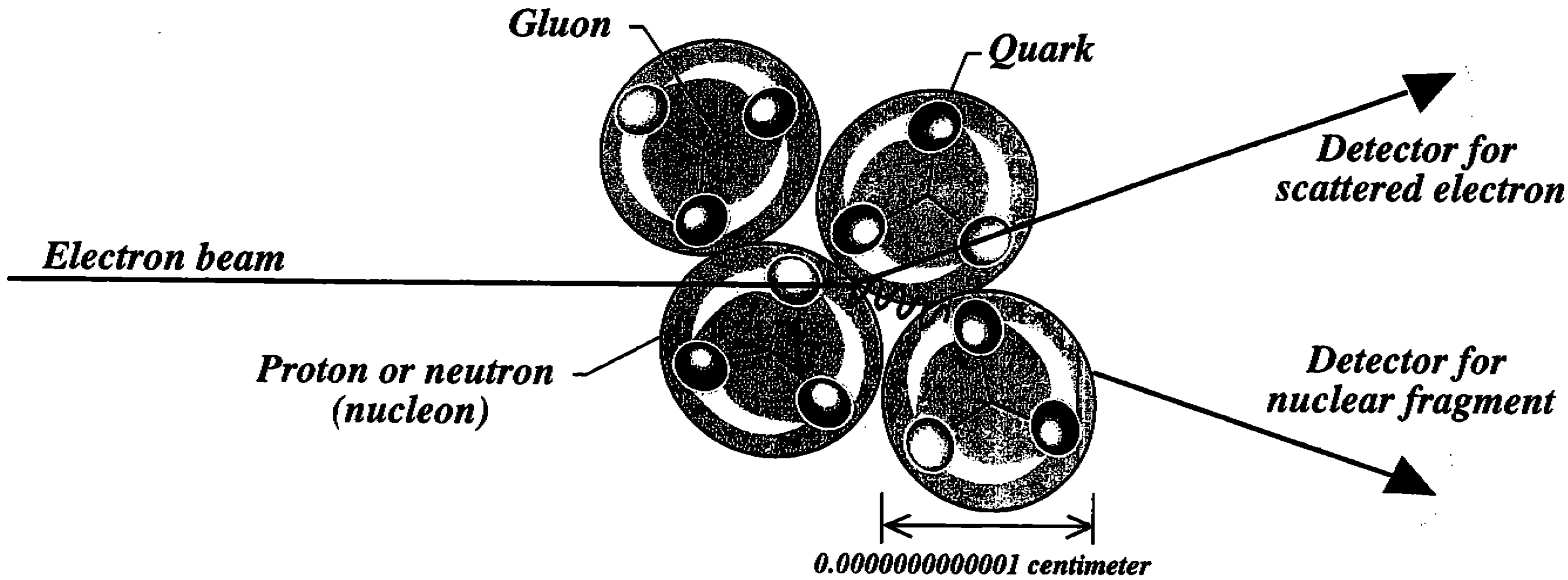
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scattered electron
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