1

The Rise of Accelerators

Accelerators are machines that use electromagnetic forces to increase the energy of charged particles. In modern machines, the velocities of the particles can approach very close to the velocity of light, that special relativity tells us is the maximum possible. To be clear in this limiting case on what we mean as acceleration, we need to be familiar with the relativistic relations among velocity, energy, momentum and mass, as well as the units that are commonly used to express them quantitatively.

Velocities are conveniently given in terms of the fraction of the velocity of light:

$$\beta = v/c\,, \quad \text{where } c = 3 \times 10^8 \text{ m/sec}\,.$$

A particle of fixed mass m has rest energy mc^2. If it is moving, it also has kinetic energy which depends on its velocity. The total energy of a particle, rest energy plus kinetic energy, is

$$E = \gamma mc^2 = \frac{1}{\sqrt{1-\beta^2}} mc^2\,.$$

Notice that an accelerator can increase the energy of a particle without limit as β approaches one, even though the velocity hardly increases. The particle is not actually "accelerating" much in the everyday sense of the word, even when its energy is increasing significantly. It would take an infinite amount of energy to bring the velocity up to $\beta = 1$.

Momentum, which is zero for a particle at rest, increases without limit as the particle is accelerated:

$$P = \gamma\beta mc = \frac{\beta}{\sqrt{1-\beta^2}} mc\,.$$

A PERSONAL HISTORY OF CESR AND CLEO - The Cornell Electron Storage Ring and Its Main Particle Detector Facility

If the force comes from an electric field $\vec{\mathcal{E}}$, the time rate of increase of momentum is $d\vec{P}/dt = q\vec{\mathcal{E}}$, where q is the charge of the particle. The corresponding energy increase can be expressed in terms of the voltage difference across which it travels: $\Delta E = q\Delta V$.

We find it convenient to measure all energies in terms of the voltage that would be required when the particle charge has the magnitude of the electron charge e. This energy unit is called the electron volt. One usually encounters it in multiples: keV, MeV, GeV for 10^3, 10^6, 10^9 eV. Rest energies mc^2 of particles are also measured in these same units — 0.511 MeV for the electron, 938.272 MeV for the proton — and we call it "mass" rather than rest energy. We further simplify by measuring momentum$\times c$ in the same units and calling it "momentum". When measured in these units, the relation $E^2 - (Pc)^2 = (mc^2)^2$ becomes simply $E^2 - P^2 = m^2$, the particle velocity is $\beta = P/E$, and the Lorentz factor γ becomes E/m.

One of the early motivations for accelerating particles was to improve on Rutherford's pioneering experiment, that is, to study the spatial distribution of charge or nuclear matter by scattering a beam of particles from various nuclear targets. The principle is related to that of the electron microscope, although one has to reconstruct the image mathematically rather than optically. The spatial resolution is comparable to the wavelength λ, which for a particle of momentum p is h/p (h is Planck's constant). The higher the beam energy or momentum, the finer the resolution. In other studies of nuclear structure the goal was to break up an atomic nucleus, for instance, by adding a proton to form an unstable compound nucleus. To accomplish this, the proton has to have enough energy to overcome the electrostatic repulsion of the target nucleus. In recent decades an important goal has been to study new forms of matter by using collisions of high energy particles to convert kinetic energy to mass (rest energy) in the creation of new particles: mesons, hyperons, and such. With higher beam energy, one can make more massive particles.

So for these reasons and more, the most important parameter characterizing the capability of an accelerator is not the maximum velocity it can give to a particle but the maximum energy. At the time of writing, about 1000 GeV is held by the Fermilab Tevatron proton accelerator. Almost as important is the beam intensity, the number of particles that can be accelerated per unit of time, for instance up to 10^{14} per second for the Fermilab machine. If the intensity is insufficient, you cannot detect rare processes, and measured reaction rates may be dominated by the random fluctuations of small numbers.

We should also include as a parameter the kind of particle the machine is designed to accelerate. In principle, it could be any charged particle that lasts long enough to survive the acceleration. In elementary particle physics, this means the proton or electron, and in recent years their antiparticles, the antiproton and the positron. For nuclear studies, though, we can accelerate practically any kind of ion. Heavy ions from deuterium to gold have been accelerated.

The first accelerators [1] used a DC voltage in a vaccum to accelerate protons across the gap from one electrode to the other. The maximum particle energy was limited to a few hundered keV (a few MeV in later years) by breakdown of the voltage. It was E.O. Lawrence in the 1930s who conceived the idea of circulating protons or other positive ions in a magnetic field so they could make multiple passes through a more modest electric field, gaining energy on each pass. The electric field would oscillate and the particle bunch passage through the voltage gap would be synchronized to occur at the right polarity. As the proton velocity increased, it maintained synchrony with the oscillating electric field, because the increasing momentum caused the orbit radius in the magnetic field to increase.

Lawrence's cyclotron at UC Berkeley inaugurated the era of circular accelerators and eventually a new style of experimental physics. The energy of the early cyclotrons, however, was limited to several tens of MeV. As protons become relativistic the simple proportionality of momentum and velocity breaks down and the arrival of the particle bunch at the gap gets out of phase with the voltage oscillation. But the demand from the experimenters (who in those early days were also the accelerator builders) was always for more energy. The solution was to modulate the frequency of the accelerating voltage to keep step with an accelerating bunch of protons. In the 1940s and 1950s synchrocyclotrons were built at a number of universities in the US, at at the CERN international laboratory in Geneva, Switzerland, and at the Dubna laboratory in Russia. As the energies reached several hundreds of MeV, the size of the magnet needed to accommodate the particle orbit at the highest momentum got to be a very significant cost factor, again limiting the maximum energy achievable.

This time the solution was to let the magnetic field vary in time in proportion to the particle momentum, keeping the orbit radius fixed, instead of letting the orbit spiral to larger and larger radii in a fixed magnetic field. Thanks to the principle of phase stability discovered by McMillan and Veksler in 1945, the particles would always gain momentum at the accelerating voltage gap at just the right rate to match the rate of increase in magnetic field. After the accelerator had produced a beam pulse at the peak energy, the magnetic field would return to its low starting value and the cycle would repeat with a new bunch of particles. For large energies a ring shaped magnet to accommodate the fixed radius synchrotron orbit was much more economical than providing the magnetic field over the full area enclosed by the maximum radius in a synchrocyclotron. The first synchrotrons accelerated electrons, and such machines were built with energies of hundreds of MeV at several universities, including Cornell. Proton synchrotrons of several GeV energy were built starting in the late 1950s. The cost had become too high, though, for a single university, so some, such as UC Berkeley, became national laboratories and others formed consortia to run new national laboratories — Brookhaven on Long Island and later Fermilab in Illinois, with funding from the Department of Energy, formerly ERDA, and before that, the AEC. By the 1970s the only remaining frontier-energy

A PERSONAL HISTORY OF CESR AND CLEO - The Cornell Electron Storage Ring and Its Main Particle Detector Facility

accelerator not at a DOE national laboratory was the 10 GeV electron synchrotron on the Cornell campus, supported by the National Science Foundation.

Meanwhile, outside the US, proton synchrotrons came into operation at CERN (on the Swiss–French border), Saclay (France), Rutherford Laboratory (England), Dubna and Serpukhov (Russia), and KEK (Japan). Electron synchrotrons were running at Frascati (Italy), Bonn and Hamburg (Germany), Daresbury (England), and Lund (Sweden).