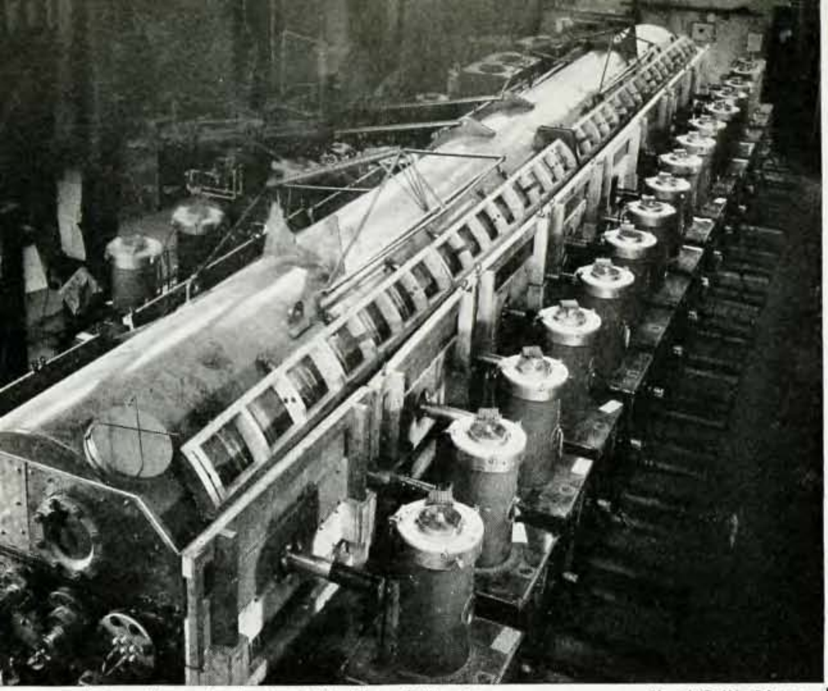
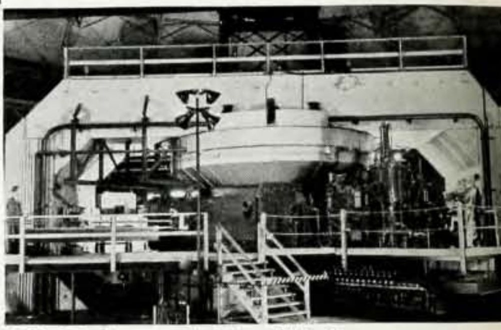


Proton Linear Accelerator at Berkeley, California *U. of Calif. Photos*

The enormous speeds with which atomic particles smash into target materials are attained as much by ingenuity as by bigness. The autho a physicist in the University of California's Radiation Laboratory, describes how different kinds of atomic accelerators operate.



184-inch Cyclotron at Berkeley, California

ACCELERATING ATOMIC PARTICLES

by ***W. M. Brobeck***

In the last fifteen years, in most of the important universities and scientific institutions of the world, there have been built in physics laboratories a great many large and complicated machines which project beams of fast-moving atomic particles. These machines—the cyclotron, the betatron, the synchrotron, the synchrocyclotron, the linear accelerator, and the Van de Graaff generator—in their seeming superfluity hint that the physicist does not have what he wants, but that he is looking for it very hard.

He is. He is looking for higher and higher energies with which to probe the nucleus and nucleons, the stuff of which the nucleus is made. As a probe, the accelerators shoot streams of electrically charged particles at speeds that can be measured in millions of miles per hour. Different kinds of accelerators shoot different kinds of particles at different kinds of targets. Sometimes they may even give different kinds of answers. So there is a great variety of work that must be done.

The projectile particles are electrons, which are negatively charged and relatively light, or protons (the nuclei of hydrogen), which are positively charged and relatively heavy, or the nuclei of heavy hydrogen (deuterons) or of helium (alpha particles). These primary particles are sometimes used to produce secondary particles: neutrons (particles with the mass of protons but no charge), and photons (quanta of light).

To probe a nucleus one must make the particles in the beam come very close to it, or even collide. If working with electrons, one needs high speeds to smash through the electron shell surrounding the nucleus which normally would repel them. If working with positively charged particles, there is less trouble getting through the electron shell, but one needs high speeds to overcome the mutual repulsion between the particles and the positively charged nuclei of the target so that they can get close enough to react.

A second reason for high speed particles is that the more rapidly two particles approach each other, the more damage may be done to each of them when they collide. The more pieces they break into, the more can be learned of their composition.

Protons and neutrons, which together make up most of the nuclei of all the elements, have been knocked out of nuclei with the energies now used, but so far it has not been possible to knock the proton or neutron (together called nucleons) apart and find out what it is they are made of. There is some hope, however, that if still higher energies are available, billions of electron volts, for example, the nucleons themselves may disintegrate and reveal their internal structures.

All the accelerators have, in addition to the fact that they speed up beams of atomic particles, several other things in common. One of these things is the way in which the energy of any one particle in the beam is measured. It is in electron volts, a term which has to do with both electrons and volts, yet is not a measure of electricity. It is a measure of the energy of a body in motion—kinetic energy.

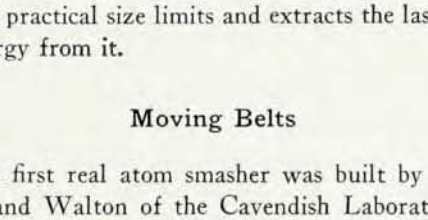
An electrically charged particle will move in an electric field, faster and faster, toward the electrode which is oppositely charged (much as a stone falls toward the earth). As the particle accelerates, its kinetic energy increases, and, if it started at one electrode and accelerated without interference, it would reach the second electrode with a kinetic energy which is measured by multiplying its charge by the voltage difference between the electrodes. If the particle has the charge of a single electron and the voltage difference is one volt, its final kinetic energy is one electron volt. One proton, which has the charge of a single electron, moving through a million volts would arrive at the second electrode with the kinetic energy of a million electron volts. An electron, which has the same charge (though of opposite sign), moving through the same electric field, would, because it is so much lighter, reach the same energy by achieving a much higher speed.

These examples not only define the energy unit, but describe the basic method of atomic acceleration: one needs a source of particles and an electric field through which the particles are accelerated. A complete accelerator must include, in addition to the electrodes which provide the electric field, an ion source where the originally neutral atoms have their electrons removed to leave the bare charged nuclei or ions, a vacuum envelope or tube surrounding the ion source, and an acceleration region. All but a few parts in a billion of the atmospheric air must be pumped from the vacuum tube to make sure the ions will not be lost by collision with air molecules.

The difficulties in making high energy accelerators now begin to emerge. How can you arrange fields of millions and millions of volts through which the particles are to move? How can you keep the machine to a practicable size? How can you keep the beam focussed so that it goes where you want it to go? And so forth. As it turns out, many of these problems have been solved by the ingenious technique of using some one part of the machine over and over and over again, which keeps the machine within practical size limits and extracts the last drop of energy from it.

Moving Belts

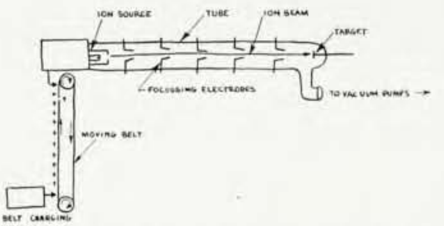
The first real atom smasher was built by Cockcroft and Walton of the Cavendish Laboratory in England and they obtained seven hundred thousand volt protons, with which atoms of lithium were split into pairs of helium atoms. The apparatus consisted of an evacuated tube with an ion source at one end and a target at the other, components common to all atomic accelerators. The voltage difference between the ends of the tube was supplied by a vacuum tube rectifier similar in principle to the type used in a home radio set, but much larger. A



SIMPLE ELECTROSTATIC ACCELERATOR

Similar to accelerator used by Cockcroft and Walton considerable number of machines of this same or similar type have been and are still being built to observe the effects of low energy particles. These machines differ in the ways of obtaining their high voltage but have in common the long, unenclosed vacuum tube.

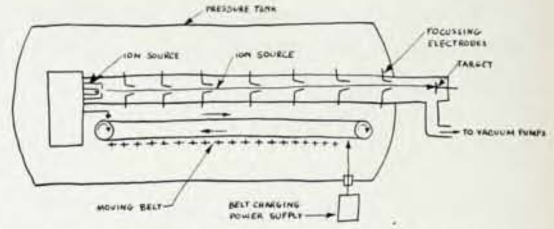
Higher energies were wanted, and the first of two improvements, which increased the available energy to the range of four to six million volts, was an electric generator, invented by Van de Graaff, of the Massachusetts Institute of Technology. It operated on the principle of the static machine, or in still simpler terms the principle of producing a spark by rubbing a cat's back with an insulating



VAN DE GRAAFF ACCELERATOR

rod. In the Van de Graaff generator a continuous belt, made of material which does not conduct electricity, travels between the ends of the vacuum tube. Electrons are sprayed on the belt at one end and removed at the other. This flow of electrons, carried mechanically by the belt, builds up the voltage difference between the two ends of the tube and the beam can then be shot through it.

The second improvement was to immerse the whole apparatus, belt, ion source, vacuum tube and all, in a tank under high gas pressure. This takes advantage of the effect that a spark will not jump as long a distance under high pressure as it will in air. One to two hundred pounds of nitrogen or air pressure, used with a little freon or sulfur hexafluoride, greatly reduces the dimensions required to prevent sparking. Pressure Van de Graaff's, as these machines are called, have the advantages of a very steady output of accurately controllable energy up to four to six million electron volts. It takes a tank about eight feet in diameter and thirty feet long to provide the clearance between internal parts required to prevent sparking in a four-million-volt machine. These tanks are often made with spherical



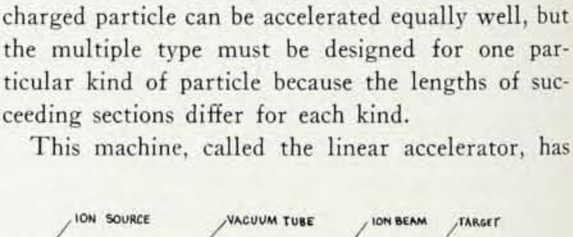
PRESSURIZED VAN DE GRAAFF ACCELERATOR

ends to resist the high pressure, and with greater diameter at the high voltage end of the tube, resulting in the pear shape familiar to many readers. Larger machines can undoubtedly be made, and two twelve-million-volt Van de Graaff's are now being built, but hundreds of millions of volts are obviously out of the question for this method.

Over and Over Again

To reach beyond the limits of the Van de Graaff machine a different approach was needed. The idea arose of using the same accelerating voltage over and over again. In an elementary form one might imagine using a number of Van de Graaff machines, one after the other, each one turning on as the ions entered to draw them into the accelerating electrode, and then reversing the voltage while the ions drifted through to push them out to the next stage. When this scheme is considered in more detail it appears that the ions move so fast the voltage must be reversed very rapidly, in fact millions of times a second. Further, to provide for the increase in speed of the ion, the length of succeeding tubes must increase. In the machines previously considered any charged particle can be accelerated equally well, but the multiple type must be designed for one particular kind of particle because the lengths of succeeding sections differ for each kind.

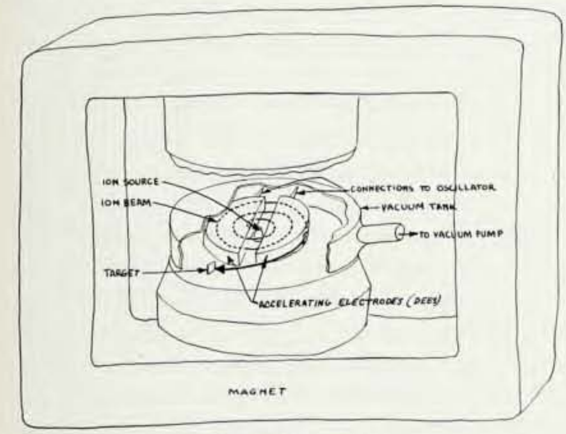
This machine, called the linear accelerator, has



LINEAR ACCELERATOR

been built to accelerate electrons to two million volts, and protons to thirty-two million. However, they have not proved as popular as the magnetic accelerators to be described later, principally because it is difficult to hold the particles in line inside the tube and in step with the reversals of the voltage.

Using the same voltage over and over again was one saving, the next step was to use the same acceleration tube over and over again. This was done in the cyclotron. The ions are returned from the output to the inlet end of the accelerating tube and so pass again and again through the same voltage drop and through the same electrodes. Each time they arrive with higher speeds, and are then further accelerated in another turn about the machine. This can be done because a magnetic field can make an ion move in a circular path.



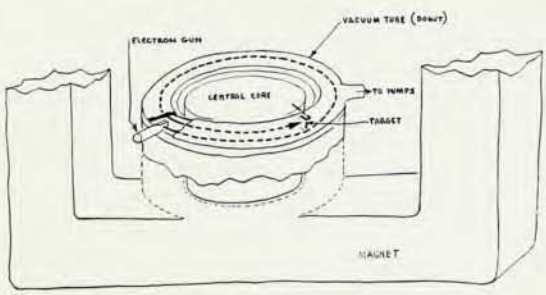
CYCLOTRON

FM cyclotron is same except oscillator provides a varying frequency and generally only one dee is used.

Lawrence, of the University of California, whose idea this was, installed semicircular electrodes between the poles of a powerful electromagnet and placed the ion source in the center. The ions spiral outward and pass through the electrodes on every revolution. The time it takes an ion to make its revolution in a magnetic field depends only on its mass and charge and not directly on its speed, so a constant reversing frequency is used. The ions keep spiralling out continuously until they strike a target at the outer edge of the spiral or are peeled off by a deflector.

The cyclotron, as Lawrence named his device, had extended the range of energies from the limit of the Van de Graaff machine to the order of fifteen million electron volts before the war and larger machines were then under construction. At that time a problem began to appear. As the ions approached the speed of light, they increased in mass—relativistic mass—and they began to fall out of step with the voltage reversals! Pessimists predicted that twenty to thiry million would be the practical energy limit for the cyclotron. This limit has since been removed by applying the synchrotron principle to the cyclotron. This will be described later.

The cyclotron is suited to accelerating heavy particles such as protons and the nuclei of heavy hydrogen and helium (deuterons and alpha particles) but not electrons. However, another type of magnetic accelerator was also successfully developed for electrons. This was the betatron, first suggested by



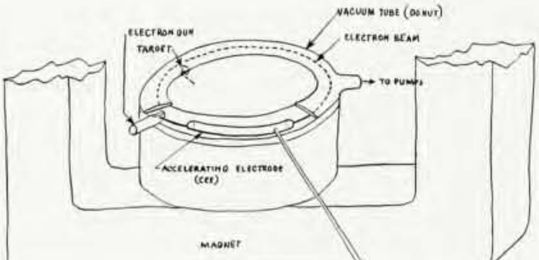
BETATRON

Wideroe in Germany and developed by Kerst of the University of Illinois. Its name is derived from the original description of electron beams as beta rays. In this machine the magnetic field was used not only to hold the electrons in a circular path but to produce the acceleration as well! The principle can best be described as that of a transformer where the primary is the magnet coil and the secondary the electron orbit. The magnet steps up the voltage of ten thousand or so supplied to its coils, to as much as one hundred million volts effective on the high speed electrons. The betatron holds the particles at a constant radius rather than causing them to spiral outward as in the cyclotron. Correspondingly, the magnetic field must rise each time a group of particles is accelerated, in contrast to the steady magnetic field of the cyclotron. These machines, made in considerable numbers in the twenty-million-electron-volt range, are our most energetic sources of x-rays, produced when the electrons strike the target.

Keeping Step

At the end of the war Veksler of the Academy of Sciences, USSR, and McMillan of the University of California independently suggested an alternative type of electron accelerator, more like the cyclotron and linear accelerator and more economical of iron than the betatron. This device, the synchrotron, passes the particles through a hollow electrode, as in the cyclotron, and so does not have to accelerate them with the magnetic transformer action of the betatron. But the synchrotron keeps the particles bunched in a circular path, as in the betatron. It had been thought that the particles would not stay in step with the voltage reversals but McMillan and Veksler showed that stability could be obtained and derived the equations governing this condition of synchronism which is the basis of the name of the machine.

Electrons are used in the synchrotron because they go so fast their velocity is practically equal to that of light during most of the acceleration period and hence, because their time per revolution is substantially constant, the frequency of electrode voltage reversal can be made constant. A synchrotron is in operation which develops seventy million electron volts and a number of machines are now under construction for energies up to three hundred million.



SYNCHROTRON

(Magnet is smaller than that of betatron as no central core is required)

The synchrotron principle of stable acceleration has also removed the energy limit on the cyclotron, as has been mentioned. The synchrotron theory showed that it is only necessary to vary the frequency of reversal of accelerating voltage in approximate proportion to the ion's increase in weight, because it turns out that the exact rate of variation is not important. This feature was applied to the four-thousand-ton cyclotron at Berkeley, making it possible to develop two hundred million volts instead of the sixty million that had been previously planned. The limits on cyclotrons now are only the costs of constructing the huge magnets required for even higher energies.

The cyclotron is today the most powerful atom smasher but it is only natural that the physicists should look beyond their present huge machines to find the possibilities of extending their principles, and incidentally their budgets, to the limit. Several laboratories are considering machines for voltages up to ten billion and in fact one machine for one billion three hundred million volts is well under construction by Oliphant in England. For this range the preferred machine is a synchrotron, designed to accelerate protons rather than electrons. The principle is identical to that of the electron synchrotron, with the added requirement that both the magnetic field and the frequency of reversal of the electrode voltage must be varied as the velocity of the proton increases during acceleration. Problems in the design of these machines are principally economic, since the physical principles have been well tested on the smaller types. For ten billion volts a ring-shaped magnet about two hundred feet in diameter and weighing perhaps ten thousand tons is needed. From its production of billions of electron volts (Bev), this machine is called by some the bevatron. The completion of one or more of these machines in the next few years should certainly break up the so-far-impregnable nucleon or indicate why it cannot be done.

HARWELL'S VAN DE GRAAFF

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