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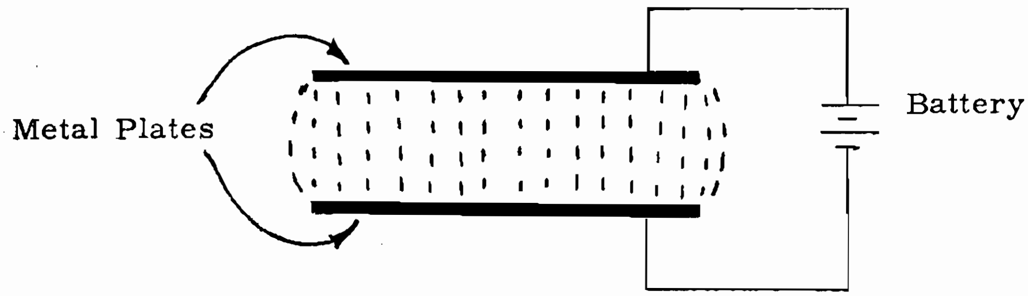
A GUIDE TO PARTICLE ACCELERATORS

F. T. Cole
Midwestern Universities Research Association

A particle accelerator is an instrument used mostly in physics research; its purpose is to provide particles of high energy for what are popularly called "atom smashing" experiments. In these experiments the accelerated particles are used to bombard a target of atomic nuclei. The fragments which come from the bombarded nuclei are studied in an attempt to learn more about the forces which hold nuclei together and about the strange new particles created by the bombardment. This discussion will concern itself with the method by which particles are accelerated rather than the experiments done with the accelerated particles.

The particles accelerated are usually electrons or protons, which, together with the neutron, are the basic constituents of matter. These particles can be accelerated and contained inside the accelerator during the acceleration by forces which act on their electric charges. It is a fact of nature that electrons and protons all have the same electric charge, while neutrons have no charge, so do not experience the same forces. Particles with electric charge experience forces when they are in an electric field or when they move in a magnetic field. An example of an electric field can be constructed by separating two metal plates by some distance and connecting a battery between them, as shown in Sketch I.



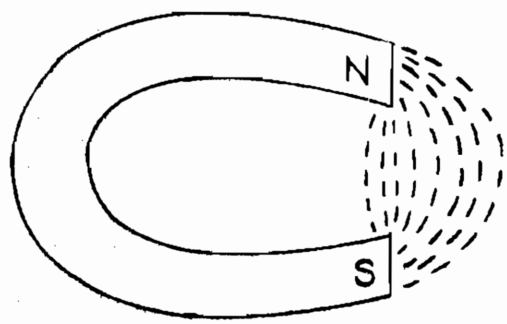
Sketch I

The dashed lines represent the electric field; a charged particle feels a force along the direction of these lines. Whether the force is down or up depends on whether the charge is positive, as is a proton's charge, or negative, as is an electron's charge. The direction of the force can be reversed by reversing the connections to the battery. If a source of alternating (A. C.) voltage is applied instead of the battery, a charge will feel a force first in one direction, then in the other, as the voltage and the electric field reverse direction.

The simplest possible accelerator can be made by putting a source of particles near one plate and accelerating them with the voltage supplied by the battery toward the other. If the proper hole is provided in the second plate, the particles will pass through it and can be used for an experiment.

The energy of an accelerated particle is usually measured in electron-volts, abbreviated ev. A million electron volts is an Mev and a billion electron volts is a Bev (Gev in Europe, where a billion is a million million, rather than our thousand million). If the simple accelerator above has a one volt battery, it gives electrons an energy of one ev. Protons gain the same energy, since they have the same charge, though of course they are accelerated in the opposite direction.

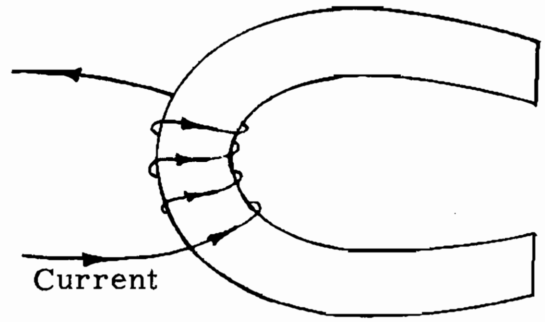
A simple example of a magnetic field is the horseshoe magnet shown in Sketch II. The dashed lines represent the magnetic field, just as the lines of Sketch I represent an electric field, but the force on a charge is different in several ways from that due to an electric field. First, a charge must be moving to feel a force from a magnetic field. Second, the force is proportional to that part of the charge's velocity which is perpendicular to the



Sketch II

magnetic field lines. A charge moving along the field lines feels no force. Finally, the force is perpendicular to both the velocity and the magnetic field. For example, a positive charge moving into the paper from above would feel a force pulling it to the left, into the horseshoe.

A magnetic field can be also made by an electric current. The field between the tips of the horseshoe magnet can be increased a great deal by wrapping a wire around the horseshoe, as shown in Sketch III, and sending a current through it. The magnet of Sketch III is actually rather similar in shape to the magnets of a synchrotron, an accelerator we shall discuss below.

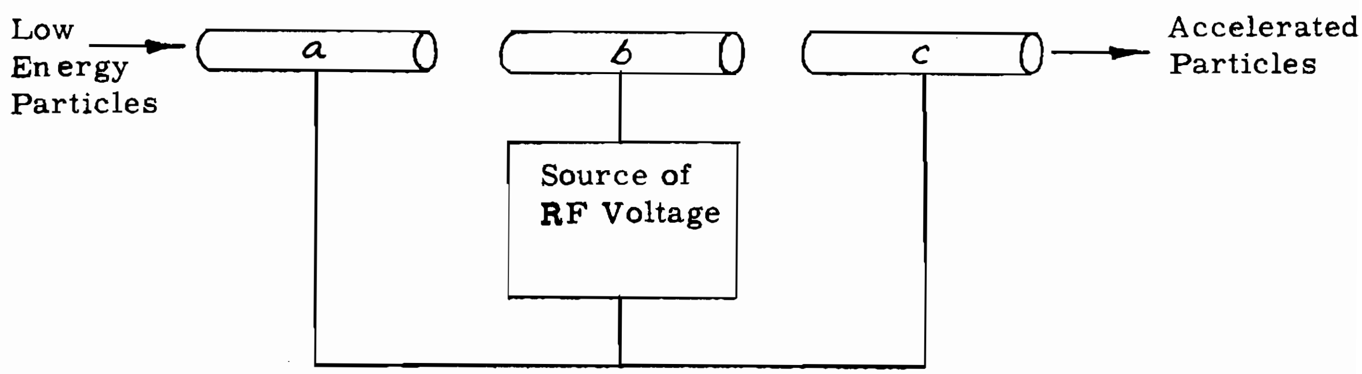


Sketch III

An x-ray machine is a particle accelerator; it accelerates electrons by a high voltage which strike a target and create x-rays. There are other accelerators, called "Cockcroft-Walton" and "Van de Graaff" accelerators after the men who conceived them, which use a high voltage to accelerate particles. Such devices are limited in the energy they can reach. An x-ray tube or a Cockcroft-Walton machine is limited to energies of about 1 Mev, while a Van de Graaff accelerator can reach energies of about 10 Mev.

It is very desirable for physics experiments to go much higher in energies than these relatively simple devices will allow. The basic principle which has proved most useful is what is sometimes called a "resonance" accelerator. In such an accelerator an A. C. voltage alternating at radio frequency (rf) is used to accelerate the particles, rather than the D. C. fields above. The particles are shielded from the effects of the rf voltage by metal conductors during the time when the rf voltage is negative and would decelerate the particles. The particles go through the same accelerating voltage many times.

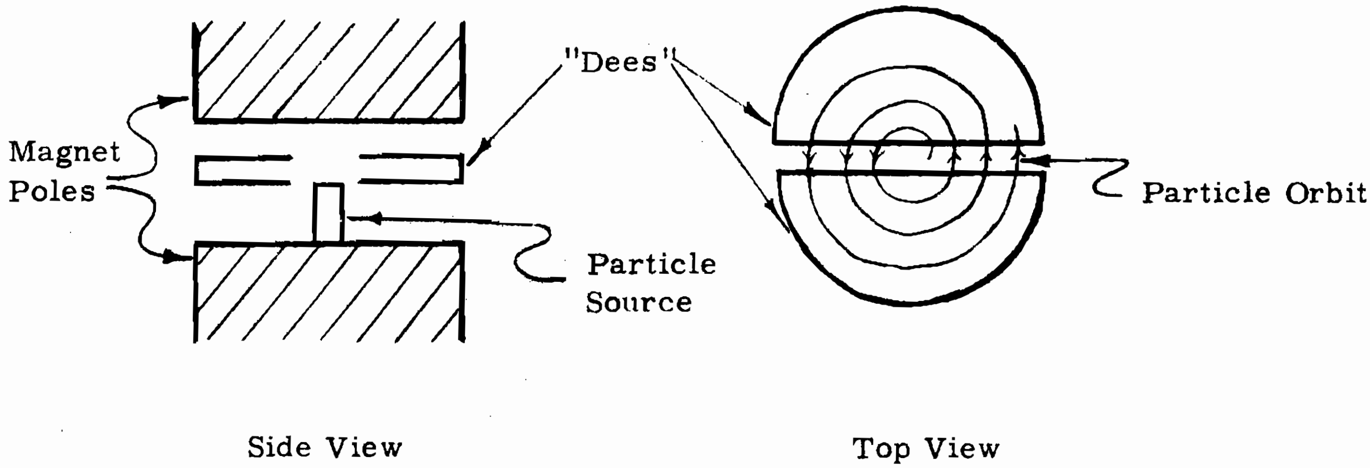
The first resonance accelerator was a linear accelerator, called "linear" because particles move in a straight line. It was conceived by Wideröe in 1927. It is shown in Sketch IV. The charged particles are



Sketch IV

accelerated by the voltage appearing at the gap a-b. Then they move through the hollow conductor b, which shields them from the rf voltage while it has the wrong sign. The frequency of the rf voltage is chosen so that when the particles appear at the gap b-c, they are again accelerated by the voltage. It is possible to give the particles twice the energy which they would gain from a single gap traversal. The frequency of the rf is resonant with the frequency at which particles appear at the gaps, which is where the name comes from.

A quite different way of producing this resonance was conceived by Lawrence in 1930. This accelerator, which is called the "cyclotron," uses a magnetic field to bend the particles in circles so that they traverse the same gap many times. The essentials of a cyclotron are shown in Sketch V. The vertical magnetic field in a cyclotron bends the particles in circles



Sketch V

often called "orbits." The rf voltage appears between the "dees," which are hollow semi-circular metal conductors. The dees shield the particles from voltages which would decelerate them. Every time a particle crosses the gap between the dees, it is accelerated. As it gains energy, it speeds up and spirals out to larger radius. It does this in such a way that its frequency of revolution, the number of times it goes around the circle per second, stays the same for all energies. The same rf voltage accelerates particles of many different energies.

The limit on the energy a cyclotron can reach comes from the theory of relativity. As a particle goes to higher and higher energy, its mass begins to change and its frequency of revolution begins to drop. It then falls out of step with the rf voltage and is no longer accelerated. Cyclotrons of conventional design are limited to about 20 Mev by this effect.

An entirely different way of achieving high energies was developed by Kerst in 1940. This device, called the "betatron" is very similar in principle to an A. C. transformer. A changing current in the primary winding of a transformer produces a voltage difference in the secondary winding. In a betatron a circulating beam of electrons is the secondary winding. The particles of this beam are accelerated by the voltage difference.

The betatron has another major difference from the cyclotron. Instead of being constant, the magnetic field which guides the particle in circles changes in step with the change of energy of the particles so that the radius of the particles' circle stays the same, instead of changing so that the particles follow a spiral.

Betatrons of up to 300 Mev have been built and used extensively for physics experiments, as well as for producing very powerful x-rays for medical and metallurgical work. The limit in energy is economic; the cost of iron for the transformer core begins to be very large and other methods of acceleration take over.

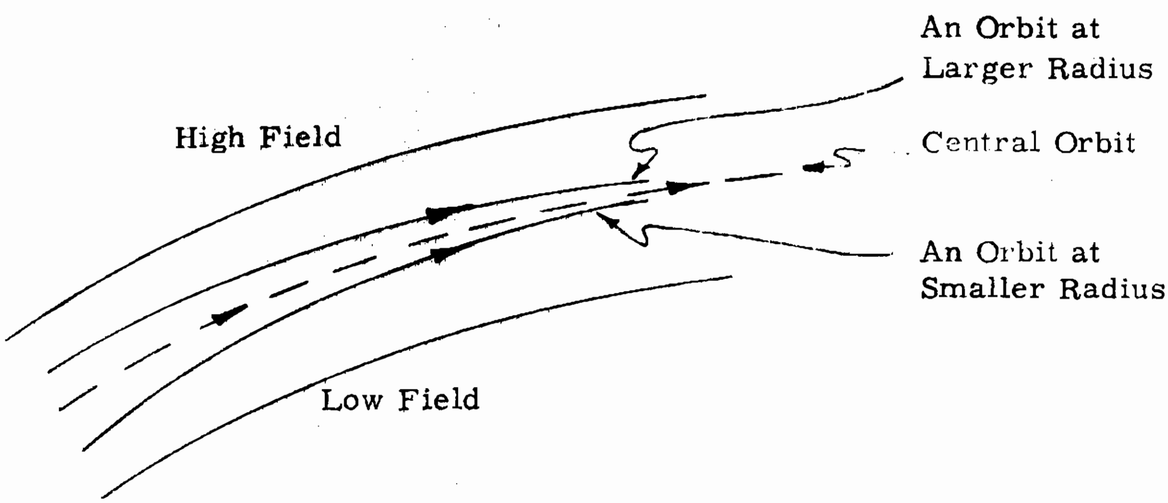
The principle which overcomes the relativity difficulty of cyclotrons was discovered independently by Veksler and by McMillan in 1946 and 1947. Technically, it is known as the "principle of phase stability." The frequency of the rf accelerating voltage must change as the revolution frequency of the particles changes to keep in step, or acceleration will no longer take place. But if the rf follows one particle, it will not follow exactly those which have somewhat different energy. Veksler and McMillan showed that if the frequency of the rf voltage is varied to follow the frequency of revolution of a particular particle, which is called "synchronous," other particles whose energies are initially not too far from that of the synchronous particle will be accelerated and will remain close to the synchronous particle in energy, so that they all gain in energy together.

A cyclotron whose rf voltage changes frequency in this way is called a "synchrocyclotron" or a "frequency-modulated (fm) cyclotron." Synchrocyclotrons have been built almost up to 1 Bev in energy.

The limit is again economic. The cost of the iron for the magnet which produces the guide field begins to exceed reasonableness. What is done is to use a guide field like that of the betatron. As the particles are accelerated by the rf voltage, the magnetic guide field changes so that the circle of the particle orbits keeps constant radius. Then only a doughnut-shaped ring of field needs to be produced, rather than the whole circle of the cyclotron. This device is called a "synchrotron." The Cosmotron at Brookhaven National Laboratory (3 Bev) and the Bevatron at the University of California Radiation Laboratory (6 Bev) are synchrotrons, as is the 10 Bev accelerator in Russia.

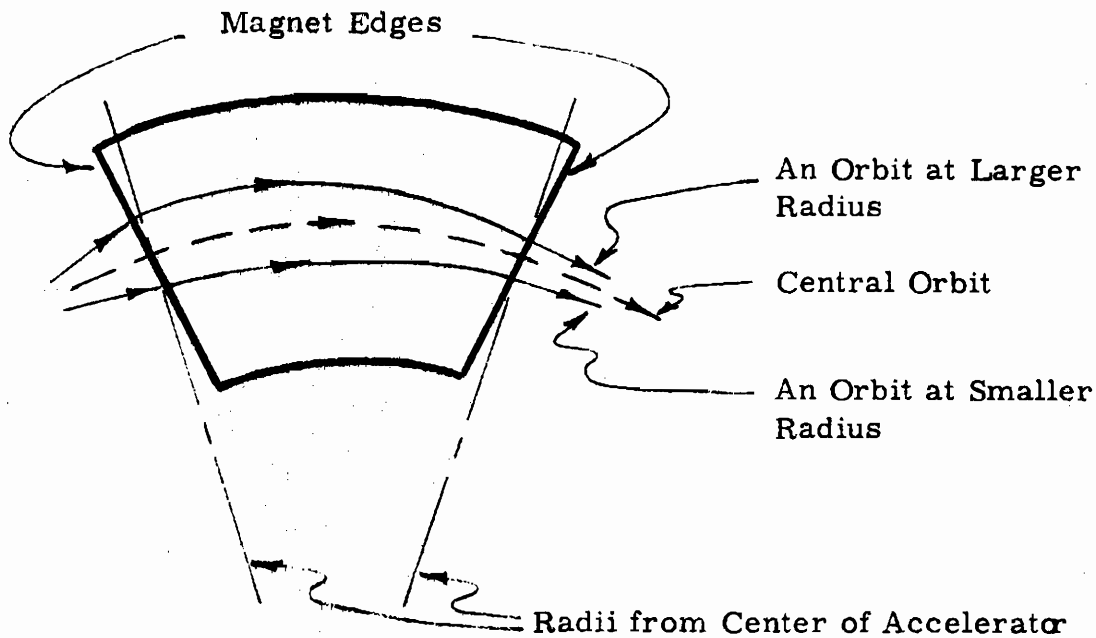
In order to bring out the later developments of accelerators, we must introduce the idea of focusing. During the course of acceleration, particles travel many thousands of miles. Not all particles can be injected on exactly the correct orbit. In addition, small magnetic field errors which arise from inhomogeneities of the iron, from constructional errors or from physical misalignment of the magnets cause the particles to stray from the correct orbit. If there are no focusing forces to return particles toward the orbit, they will be lost by hitting the walls of the vacuum chamber and the accelerator will be valueless.

In order to bend a particle toward the correct central orbit, it must go through a different magnetic field than it would on the central orbit. The magnetic field can differ from that on the central orbit in two ways. First, it can differ in magnitude, and second, it can differ in the length of field through which the particle goes. The first of these is known technically as "gradient focusing," while the second is known as "edge focusing." Sketch VI shows a variation of field magnitude with radius. When a particle at a larger radius sees a stronger field, it is bent inward more sharply than the central orbit and so moves toward it. If a particle at a smaller radius sees a weaker field, it is bent less sharply than the central orbit, so that it also moves toward it.



Sketch VI

The next sketch shows a variation of field length with radius. A particle at a radius larger than that of the central orbit goes through a greater length of field and is again bent more sharply than the central orbit, so that it moves toward it. A particle at smaller radius goes through a shorter length of field and is bent less sharply than the central orbit, so that it moves toward it.



Sketch VII

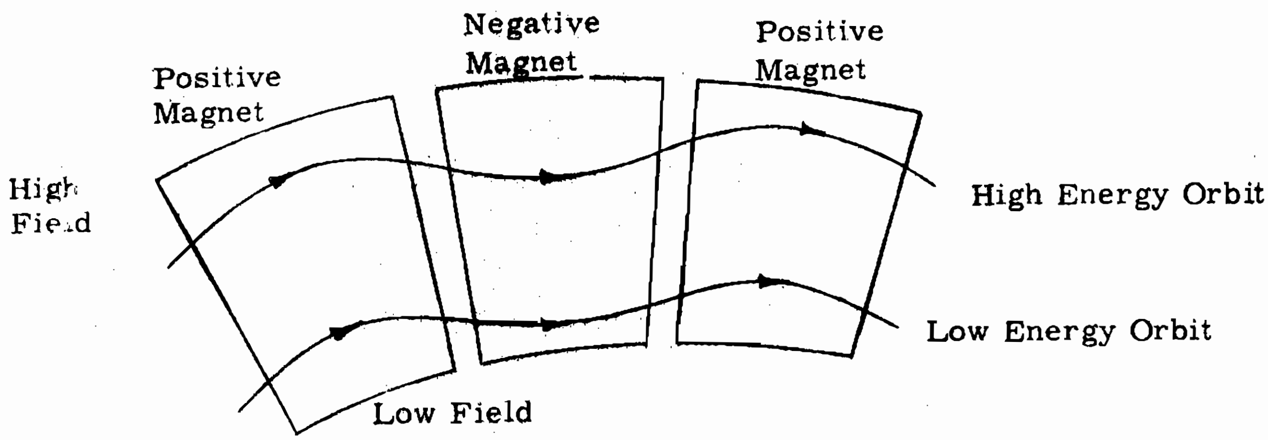
In the first case, the field varies with radius, while in the second case, it varies with angle around the accelerator. In both cases, a detailed examination shows that focusing perpendicular to the plane of the paper decreases as focusing in the plane of the paper increases. A compromise must be made to insure that there is focusing in both dimensions.

For example, if the field increases with radius, the relativity difficulty of cyclotrons can be overcome, but focusing perpendicular to the plane of the orbit is lost.

All the synchrotrons built up to 1954 are what is termed "weak focusing" accelerators. Their focusing consists completely of gradient focusing and is of a strength so that the wavelengths of the focusing oscillations are about the same as the circumference of the accelerator.

In 1951 a new method of focusing was discovered independently by Christophilos and by Courant, Livingston and Snyder. If the gradient varies around the accelerator, the focusing, called "alternating gradient" (A. G.) focusing, can be made much stronger. There are now several wavelengths of focusing oscillation per circumference of the accelerator. This means that particles stray a much smaller distance from the central orbit. Since the whole region where particles moves must be essentially surrounded by the iron of the magnets, smaller oscillations require less iron and are therefore a great saving. At the present time two proton synchrotrons of 25 Bev energy are nearing completion, at Brookhaven National Laboratory and at CERN in Europe. These accelerators would have been economically unfeasible without A. G. focusing.

A. G. focusing also gave rise to much more profound thinking about particle orbits in accelerators. One of the most important results of this thought has been the development of FFAG (Fixed Field Alternating Gradient) accelerators. The first such accelerator was conceived independently by Ohkawa and Symon in 1953 and 1954. The important new feature is that the magnetic guide field is fixed, like a cyclotron, rather than pulsed like a synchrotron. Particles of very different energies can circulate simultaneously in this fixed field. Sketch VIII shows the radial sector FFAG accelerator.

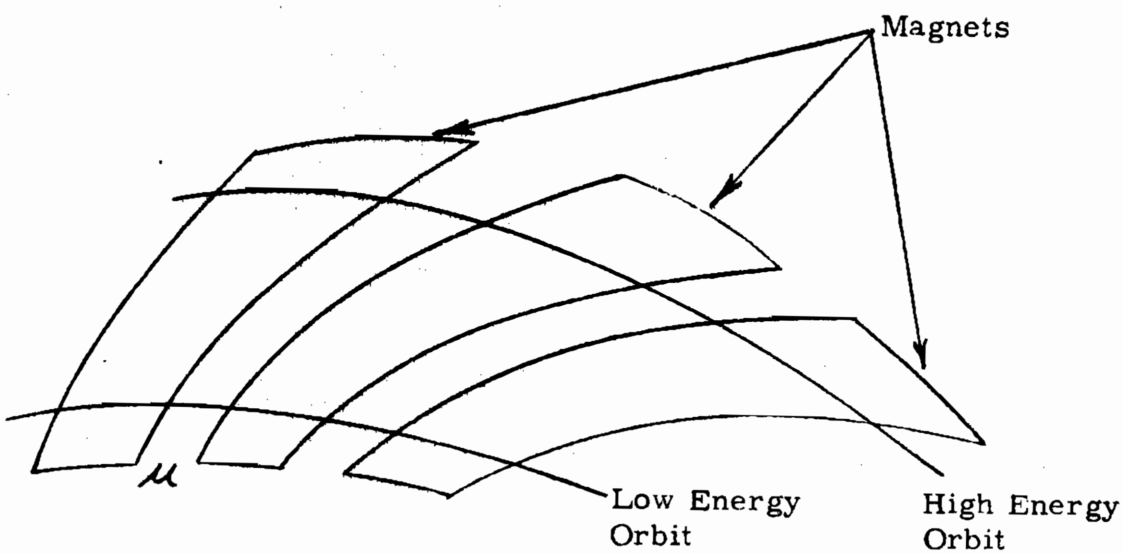


Sketch VIII

The magnetic field reverses in direction as one moves from one magnet to the next. A particle is bent toward the center of the accelrator in a positive magnet and away from the center in a negative magnet. In both positive and negative magnets, the field increases with radius, so that a particle of high energy follows an orbit which is just an expanded picture, like a photographic enlargement, of an orbit of a low energy particle. As particles are accelerated, by an rf voltage, for example, they spiral outward, as they do in a cyclotron. But there is only a dough-nut-like ring of field, as in a synchrotron, not a whole circle, so that there is a saving of iron.

The negative magnets bend particles in the wrong direction to get around the accelerator, so that the accelerator must be larger than an accelerator of the same maximum energy and magnetic field. But the negative magnets are necessary to provide focusing perpendicular to the plane of the paper. The radial sector FFAG accelerator has both gradient and edge focusing, the first because the gradient changes sign when the field does and the second because the orbits enter and leave magnets at angles with the field edges which are not perpendicular.

In 1954 Kerst discovered a focusing method which did away with the need for negative magnets. If the magnets themselves spiral outward, there is edge focusing at one edge of a magnet and edge defocusing at the other. Just as in the case of the A.G. synchrotron, the combination of focusing and defocusing effects can lead to focusing action. Sketch IX shows the spiral sector FFAG accelerator. All the magnets are positive.



Sketch IX

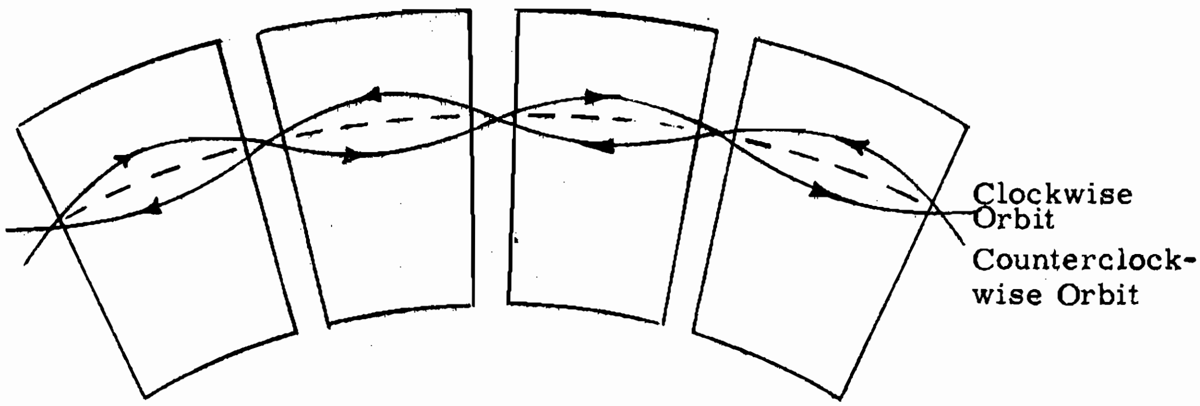
One can also design FFAG cyclotrons which can accelerate particles to relativistic energies without modulating the frequency of the rf accelerating voltage. It appears to be possible to build these cyclotrons of energies up to 900 Mev for protons.

The focusing forces in FFAG accelerators are much more complicated than those in many other accelerators. It has been impossible so far to make much progress with exact mathematical theories. A great deal of digital computation has been done to investigate particle orbits in FFAG accelerators. A computer carries out a sequence of arithmetic operations (addition, subtraction, multiplication and division) at very high speed. It remembers the sequence (if told to) and so goes through it automatically. The computer adds up the forces on a particle at some point of its path and then calculates where the particle will be after a small step. It then begins again by finding the force on the particle at its new position, and so forth. The problems of the construction of the complicated magnetic fields of FFAG accelerators are also solved by the digital computer. Accelerators can now be designed almost completely with the digital computer, rather than by trying to solve the problems mathematically.

Since the field is fixed in an FFAG accelerator, one bunch of particles can be accelerated to high energy and left to coast while another bunch is accelerated up. By means of this stacking process, a very intense beam of circulating particles can be built up. It is now possible to do experiments by bombarding two accelerated beams against each other, experiments which could not be done in the past because the beam intensities were so low that no collisions could be observed. When an accelerated beam bombards a stationary target, all the products are knocked off with high velocities in the direction of motion of the beam. A large fraction of the bombarding energy is used up not in creating the products, but in giving them their high velocities. But when two beams of equal energy collide, all their energy is available for creating new products. For example, two proton beams of 15 Bev energy colliding with each other have as much available energy as a 540 Bev beam striking a stationary target.

The first method proposed to achieve collisions of two accelerated beams was to build two spiral sector accelerators tangent to one another, so that they look like a figure eight from above. Later it was suggested that a high energy beam might be taken out of the accelerator and injected into a much simpler guide field which would not accelerate the particles, but only store them. They could then have collisions with a group of particles which are brought up to high energy in the accelerator while the first group coasts. This device is called a "storage ring."

In 1954 Ohkawa pointed out that colliding beams can be achieved in the same radial sector FFAG accelerator. If the positive and negative magnets are made equal, particles still see a net magnetic field along the central orbit giving a force toward the center, because that orbit moves radially outward into higher field in positive magnets and inward into lower field in negative magnets. The positive field along the orbit is therefore larger and so a particle experiences the force it needs to get around the accelerator. But a particle moving the opposite way around the accelerator sees opposite magnetic forces, so it just interchanges positive and negative magnets and gets around in the same way. Sketch X shows particle orbits for both directions in several such magnets.



Sketch X

The first MURA model was a radial sector FFAG, while the second was a spiral sector. The third is an Ohkawa two-beam accelerator.

Colliding beams are quite difficult to use for experiments, because of the large background of other events. At the present time the development of the accelerator itself is more advanced than the development of the particle detecting equipment for use in experiments, which makes it difficult to proceed with the construction of a large colliding beams accelerator.

During all this time developments in linear accelerators, the type first conceived by Wideröe, have also taken place. There are interesting focusing properties in linear accelerators, but most of the development has been concerned with increasing the energy gained per accelerating gap. High frequency tubes of very high power have been extensively improved in this work. An electron linear accelerator of about 20 Bev is now under serious consideration.

There have been other new ideas for guiding and accelerating particles, but these have so far not been proved practical. Taken together with the developments discussed in the above, these new ideas are certainly an indication of the great vigor of research into means of accelerating particles.