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The cyclotron is a particle accelerator conceived by Ernest O. Lawrence in 1929, and developed, with his colleagues and students, at the University of California in the 1930's. His goal was to produce beams of high energy ions, without using high electrostatic voltages, to study their reactions with atomic nuclei. Since then over a hundred cyclotrons of greatly differing sizes, energies, and other properties have been built for a continually growing variety of uses. In addition, the cyclotron is the prototype of a wider class of magnetic resonance accelerators, including synchrocyclotrons, synchrotrons, microtrons, and several forms of cyclotrons with azimuthally varying fields.

By 1940 cyclotrons had been built and used at many laboratories throughout the world. Exemplified by the 60-inch cyclotron at Berkeley, their principal components were: a dc electromagnet having circular pole pieces with a magnetic gap small compared to their diameter, producing a nearly uniform axially symmetric magnetic field; two hollow flat D-shaped copper electrodes (dees) placed in the magnet gap, open toward each other, with a small space (dee gap) between them along a diameter; an electric field produced across the dee gap, oscillating at a constant radiofrequency (rf), driven by an external oscillator; a vacuum tank within the magnet gap, enclosing the dees and their supporting structures (dee stems) used as resonant lines; an ion source (electric discharge) between the dees at the center, supplied with a small flow of neutral gas; internal targets to be bombarded at large radii, and a deflection system to bring ion beams outside the accelerator. See Figure 1.

The operation depends on the cyclotron resonance condition: a particle of charge e and mass m moving in a circle perpendicular to a magnetic field B circulates with frequency f and angular frequency ω given by $\omega = 2\pi f = eB/m$ (SI units) which is the same for all energies, velocities, and radii for constant B and m. This can be seen from Newton's force law $F = ma$, with $F = eBv$ the centripetal Lorentz force, v the velocity, $a = v^2/r$ the centripetal acceleration, r the radius, and $\omega = v/r$. The kinetic energy at r is $T = \frac{1}{2} mv^2 = \frac{1}{2} (eBr)^2/m$. An ion making a circle around the source may gain energy, if the oscillator has this cyclotron frequency, on each crossing of the dee gap. The electric field there will reverse in each half-turn, having the tangential direction to speed up an ion each time the ion "sees" it. Between crossings the ions are shielded, inside a dee, from the electric field. Because of the resonance condition an ion will stay in step; its energy and radius will grow on every turn until it strikes a target or enters a deflector. [The cyclotron frequency of a charged particle in a magnetic field is also important in physics of the solid state, plasmas, the ionosphere, and astrophysics; see CYCLOTRON RESONANCE.]

It is not hard to get ions started at the center. They are drawn into a dee each time it is negatively charged (for positive ions), start to circulate at once, and tend to bunch at the correct phase relative to the rf within a few turns. However, they will soon drift away from the magnet midplane and strike the inside surface of a dee unless a vertical focusing force directed toward this plane is provided. To produce it the magnetic field strength B is made to decrease slightly with increasing radius, which causes the magnetic field lines to curve as shown in Figure 2. The Lorentz force, perpendicular to these lines, then has a small component directed toward the midplane, causing the ions to oscillate slowly up and down across it as they circulate. This small variation of B also serves to define well-centered circular orbits, about which oscillations in radius may occur. Their frequency is determined by the difference between the centripetal acceleration and the inward radial Lorentz force for ions which depart slightly in radius from the proper circle. These vertical and radial motions are called betatron oscillations because they were analyzed in connection with <u>betatron accelerators</u> (see BETATRON) in which the focusing actions are similar. The radial variation of B is described by the <u>field index</u> $n = -(r/B)(dB/dr)$; the angular frequencies of the betatron oscillations are $\omega_v = \omega\sqrt{n}$, $\omega_r = \omega\sqrt{1 - n}$ with ω as above. For $0 < n < 1$ both frequencies are real, giving stable motions. In cyclotrons n is small, rising from zero at the center to $\gtrsim 0.2$ near the outer edge. A resonant effect $(\omega_r/\omega_v = 2)$ can cause beam loss at $n = 0.2$ by transferring energy of radial oscillations, for which there is plenty of room, into vertical oscillations that have limited clearance within the dees.

With vertical and radial motions thus controlled, only an unwanted variation in azimuthal position, or phase relative to the rf oscillator, remains. This effect limits the energy of a conventional cyclotron, in which there is no phase stability. The small decrease in B and (particularly for light ions) the relativistic increase of mass ($m = m_o + T/c^2$, with m_o the rest mass and c the speed of light) both act to decrease an ion's frequency $\omega = eB/m$ as its energy and radius increase. Its times of gap crossings will lag more and more behind the phase of maximum electric field, and could eventually lead to crossings at times of reversed field, causing energy loss. To reach a high energy in a limited number of turns, before excessive phase lag can accumulate, the largest possible dee voltage is needed. The highest proton energy reached with such a cyclotron was 22 MeV; this required about 500 kV on the dees. Currents of 100 μA were typical, with a maximum of ~ 1 mA. Deuterons, alpha particles, and heavier ions in higher charge states were also accelerated. Such cyclotrons quickly became the leading tools of nuclear physics research. They were also used to produce radioisotopes for a rapidly growing number of applications in other fields. The first transuranium elements, neptunium and plutonium, were discovered through cyclotron bombardment of heavy targets.

Following World War II new methods were applied which extended the energy and other capabilities of circular magnetic resonance accelerators. The principle of phase stability (see SYNCHROTRON) led to several new classes of accelerators, of which the synchrocyclotron, electron synchrotron, and proton synchrotron have played important roles in research. They differ from the cyclotron by producing particle beams in pulses separated in time (with pulse repetition frequencies in the range ~ 1/10 to 100 Hz) rather than as a steady current modulated only at the radiofrequency. In synchrotrons the magnetic field strength is made to vary periodically, but the synchrocyclotron, or frequency-modulated (FM) cyclotron, has a static magnetic field. Its radiofrequency is smoothly lowered during each cycle of acceleration and is followed by that of the ions locked stably to it. Frequency modulation was first obtained using rotating capacitors but the largest machines use vibrating blades for this purpose. Lawrence's pioneering 184-inch FM cyclotron at Berkeley accelerated protons to 340 MeV and produced the first man-made pi mesons in 1948. After extensive improvements in 1956 it produces 720 MeV protons, which move at over 4/5 the speed of light, with a mass increase of more than 75%. Deuterons and alpha particles are also accelerated. Protons in the range 600-700 MeV are produced by similar machines at Dubna, U.S.S.R. and Geneva, Switzerland. These and others of somewhat lesser energies employ magnetic fields of over 2 Tesla. Pulse repetition frequencies are of order 60 Hz, and typical currents are 1 μA. Work with these machines has greatly enlarged our knowledge of nuclear and meson physics, particularly of pion and muon properties and nucleon-nucleon interactions. Also, large numbers of patients have been treated for certain conditions, particularly pituitary tumors, employing techniques developed at Berkeley.

A different method of overcoming the energy limitation of the cyclotron is based on work by L. H. Thomas in 1938, but the developments needed to put his concept and its later elaborations into practice did not begin until 1949. Because many characteristics of the original cyclotron (static magnetic field, constant rf frequency, and steady, non-pulsed beam) are retained by the accelerators that have evolved along this line they are called *sector-focused, isochronous, spiral-ridge,* or *azimuthally-varying-field (AVF) cyclotrons*; the name *fixed-field-alternating-gradient (FFAG) accelerator* has also been used. In these machines the magnetic field (averaged along a full turn of an ion's orbit) *increases* with radius just enough to offset the relativistic mass increase, matching the cyclotron frequency to that of the oscillator at all ion energies. The pole tips are carefully shaped and correcting fields produced by adjustable currents in pole-face windings called trim coils provide fine tuning so that every turn takes the same time; the orbits are *isochronous*. However, the rising field tends to make the vertical motions unstable. Field line curvature is reversed from that in Figure 2, so the averaged field index n is negative. The focusing force required to achieve net vertical stability by over-riding this vertical defocusing effect is obtained by making the orbits non-circular. This is done by introducing *azimuthal variations* in the magnetic field. Three-fold symmetry is common on smaller machines, six- and eight-fold on the largest. In some machines the gradual wave-like variations proposed by Thomas are used but in others the magnet is divided into *sectors* with field-free spaces between them, in which rf accelerating cavities are located. In either case vertical focusing forces result from interaction of the radial component of velocity with the azimuthal component of magnetic field. This effect, which occurs when an ion obliquely crosses a fringing field at a magnet edge in a magnetic spectrometer or other device, is known as edge focusing. The focusing force is not steady, but varies along the orbit and becomes a succession of impulses if the field changes at sector edges are steep.

The first experimental tests of this concept at Berkeley used electron model cyclotrons (1949-1952) to simulate 150 MeV proton cyclotron. "Thomas shims" to improve the focusing were first inserted in a conventional cyclotron at Los Alamos, New Mexico (~ 1956). The first isochronous proton cyclotron (12 MeV) was completed at Delft, Netherlands, in 1958. At many laboratories in North America, Europe, the U.S.S.R., and Japan new ideas were explored and programs were started to improve existing machines and to build new ones. In the early 1950's the designs were based on sectors or ridges whose center lines were straight along radii, as proposed by Thomas (Figure 3a). In the mid-1950's studies at the Midwestern Universities Research Association (MURA) in Michigan and Wisconsin, aimed at developing new types of high energy accelerators, resulted in the development of spiral ridge field geometries. It was found that this concept was applicable to cyclotrons, and that by spiraling the ridges or sectors (with larger spiral angle at larger radius) the focusing strength could be greatly increased and higher energies attained (Figure 3b). [See SYNCHROTRON, where "strong" (e.g. alternating gradient) focusing is described.]

The highest proton energies have been attained by the SIN (Zurich, Switzerland, 590 MeV) and TRIUMF (Vancouver, Canada, 520 MeV) machines (Figure 4). These are sometimes called *meson factories* because of their copious pion production by high current (50-100 μA) proton beams. The Canadian machine accelerates H^- ions, requiring a low magnetic field $(< 0.6\ \mathrm{T})$ to avoid stripping by the motional $(\underline{\underline{v}} \times \underline{\underline{B}})$ electric field, and therefore a large orbit radius $(\sim 8\ \mathrm{m})$, but beam extraction at any energy is easily accomplished by stripping in a thin foil to H^+ ions which come directly out of the magnet.

In addition to these large special-purpose machines, about fifty other third-generation isochronous cyclotrons of smaller size and energy but greater versatility are now operating, and others are under construction or design, in eighteen countries. Prototypes for some of these are the ORIC (Oak Ridge, Tennessee) and 88-inch (Berkeley) machines. Among the capabilities of this class are variation in extracted beam energy by changing magnetic field and oscillator frequency, injection and extraction of polarized beams, and acceleration of a wide variety of heavy ions.

Modern cyclotrons have many uses in addition to research in nuclear and particle physics. These include injectors for other machines, studies in chemistry, biology, medicine, and solid-state physics, and the production of proton-rich radioisotopes for hundreds of applications. Further innovations in cyclotron design are being studied, such as the development of compact simply-controlled cyclotrons for medical treatment and the use of superconducting magnet technology.

REFERENCES

Livingood, John J., "Principles of Cyclic Particle Accelerators," New York, Van Nostrand, 1961.

Livingston, M. Stanley, and Blewett, John P., "Particle Accelerators," New York, McGraw-Hill, 1962.

Kolomensky, A. A., and Lebedev, A. N., "Theory of Cyclic Accelerators," New York, John Wiley and Sons, 1966.

McMillan, Edwin M., chapter "Particle Accelerators" in Vol. III of "Experimental Nuclear Physics," ed. E. Segrè, New York, John Wiley and Sons, 1959.

Seventh International Conference on Cyclotrons and their Applications; Zurich, Switzerland, 1975. Proceedings (W. Joho, ed.), Basel, Birkhäuser, 1975. [Contains comprehensive discussions of all aspects of cyclotron technology and applications in biology, medicine, nuclear and heavy-ion physics, chemistry, and engineering; tabulations (pp. 640-642) of existing and planned AVF and FM cyclotrons; and references (p. 643) to Proceedings of six earlier conferences since 1959.]

Cross-references

Cyclotron Resonance; Betatron; Synchrotron

FIGURE CAPTIONS

Figure 1. Some components of a conventional cyclotron.

Figure 2. Curved magnetic field lines showing vertical focusing force.

Figure 3. Sectors of high and low fields; (a) radial, (b) spiral.

Figure 4. Separated sectors of TRIUMF H^- cyclotron (Canada).

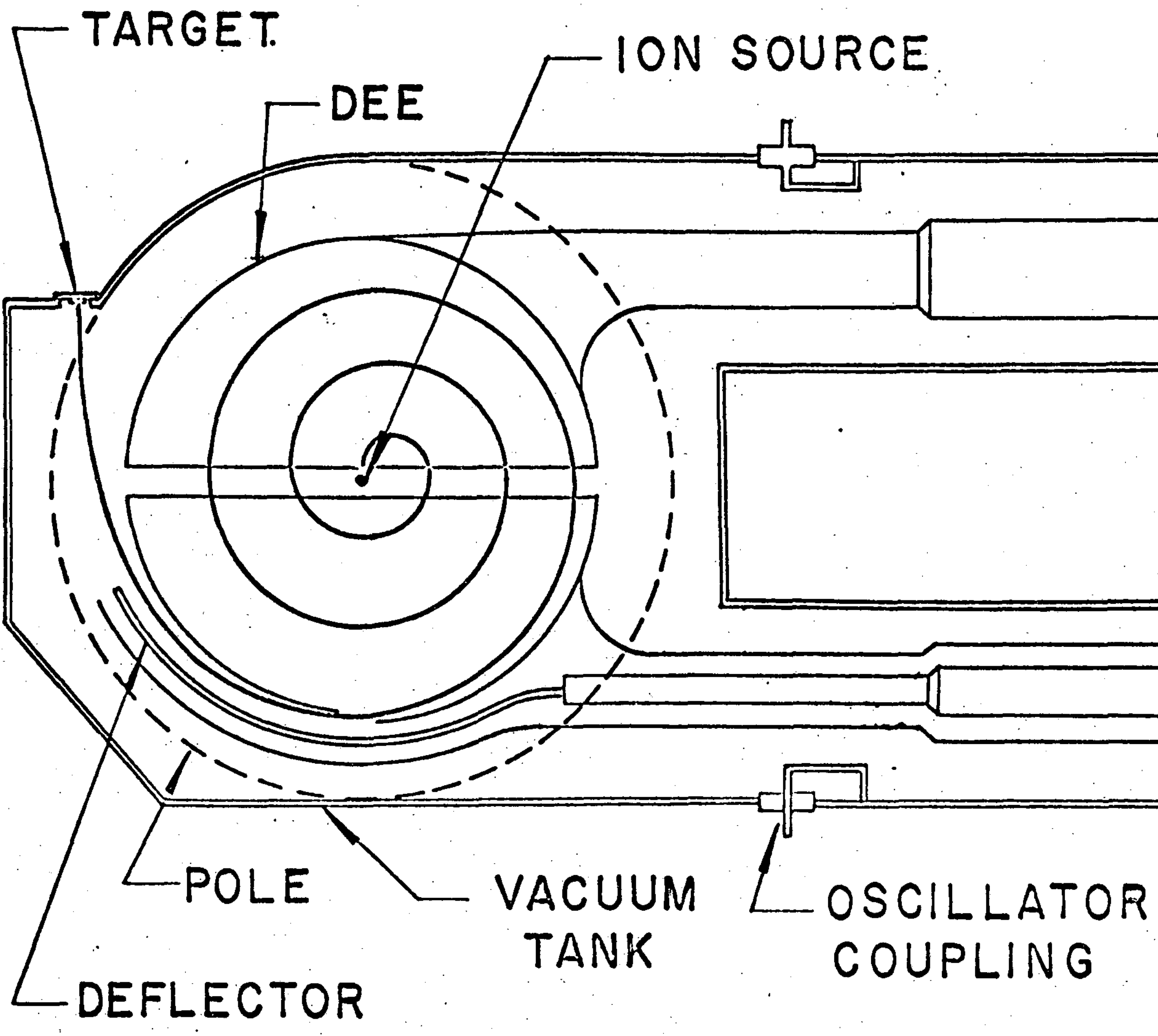

TARGET
ION SOURCE
DEE
POLE
VACUUM TANK
OSCILLATOR COUPLING
DEFLECTOR

Fig. 1

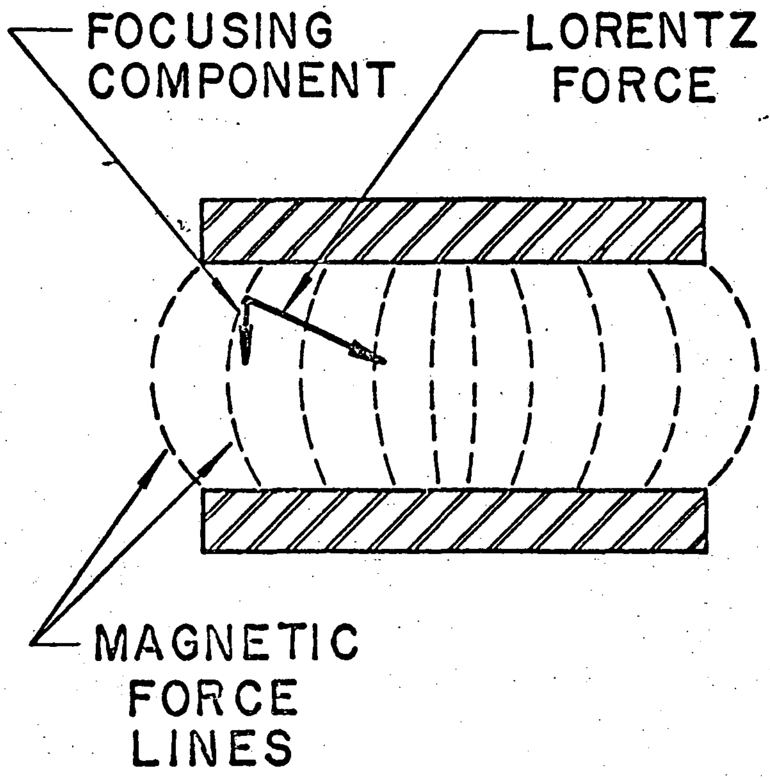
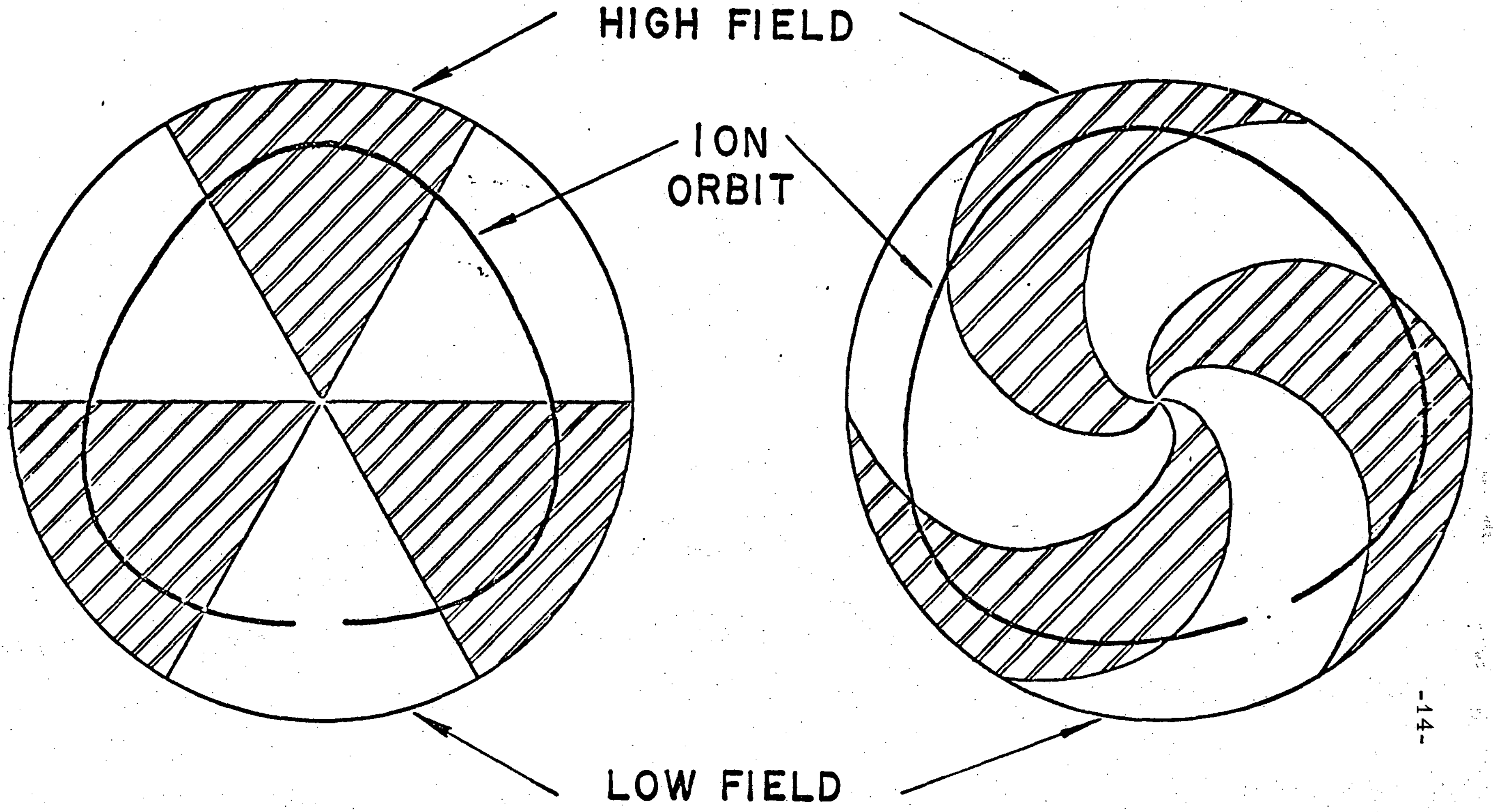


Fig. 2



(a) (b)

Fig. 3

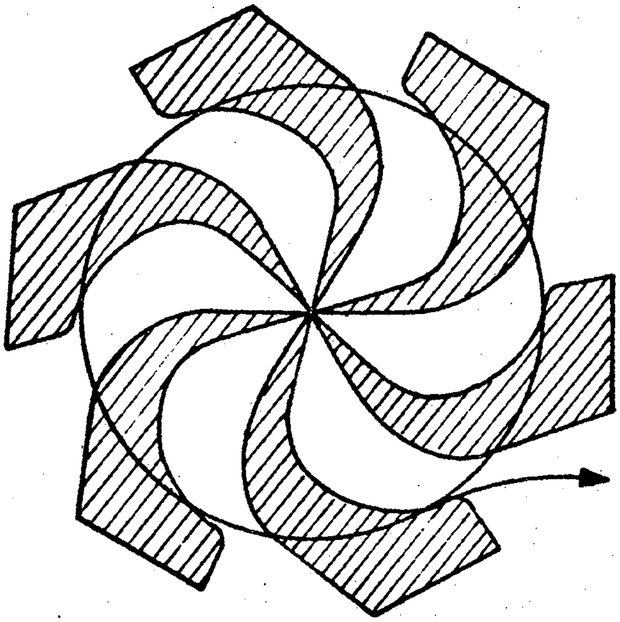


Fig. 4