Feb. 3, 1959 E. M. McMILLAN ET AL 2,872,574

CLOVERLEAF CYCLOTRON

Filed April 12, 1956 4 Sheets-Sheet 1

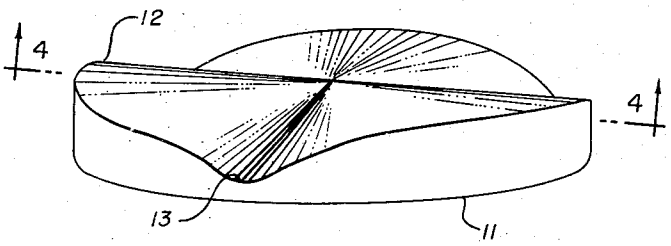


Fig. 2.

Fig. 4.

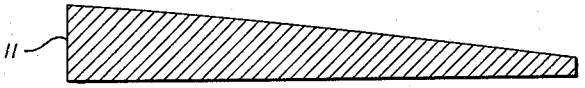


Fig. 3.

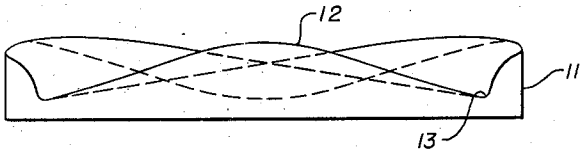
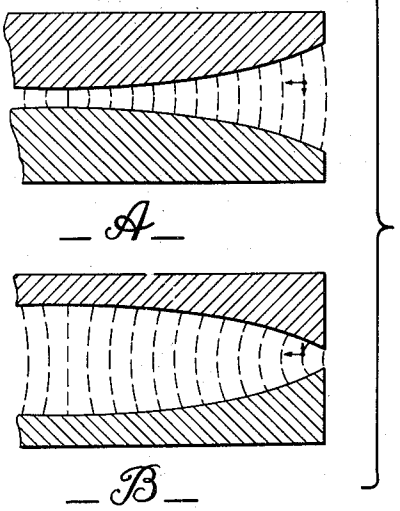


Fig. 1.



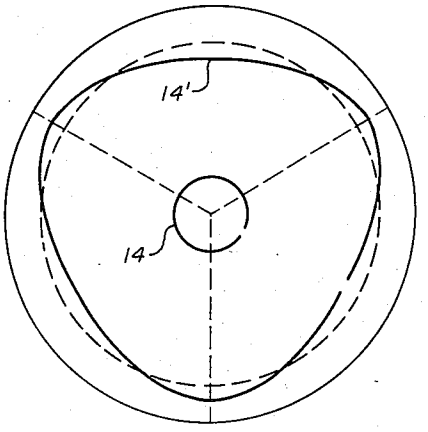


Fig. 5.

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Filed April 12, 1956 4 Sheets-Sheet 2

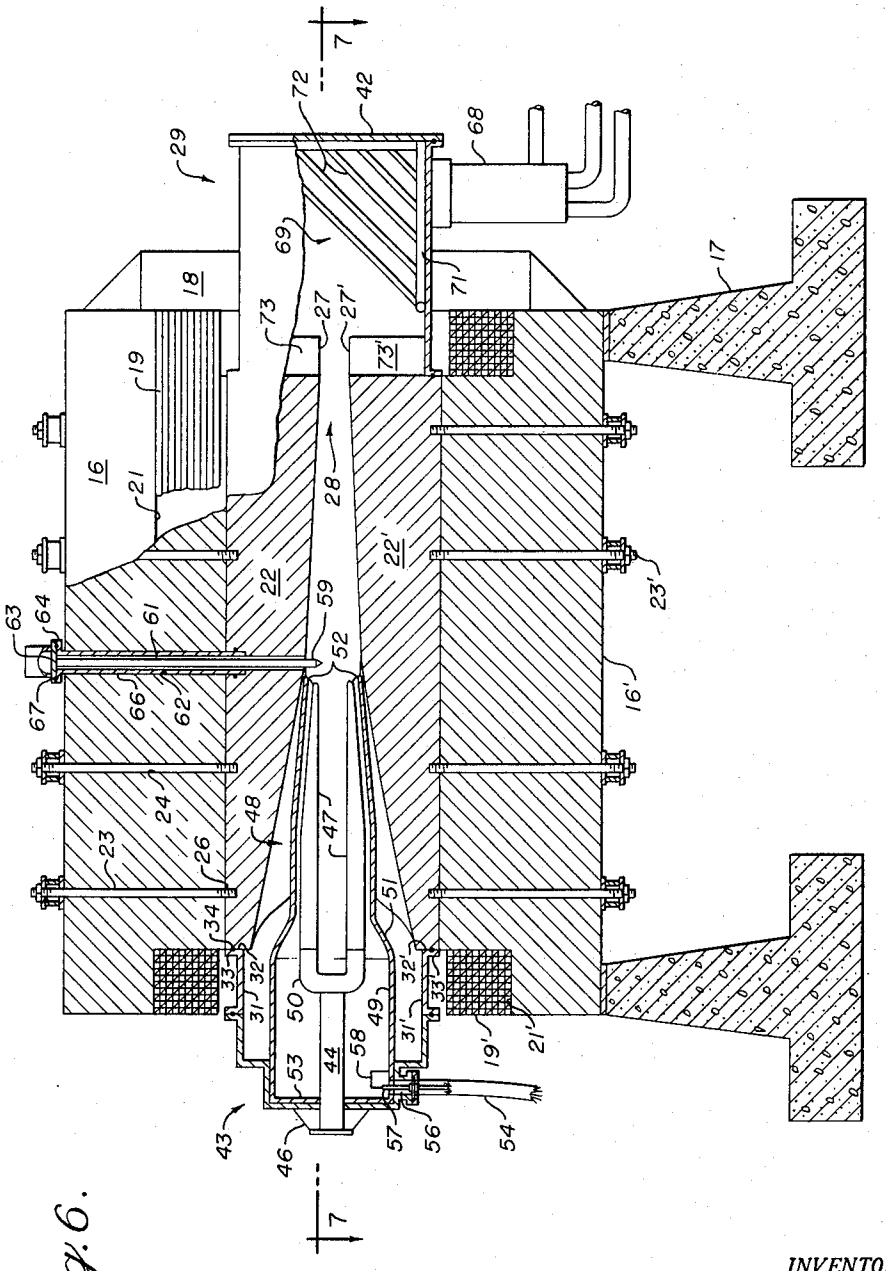


Fig. 6.

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Filed April 12, 1956 4 Sheets-Sheet 3

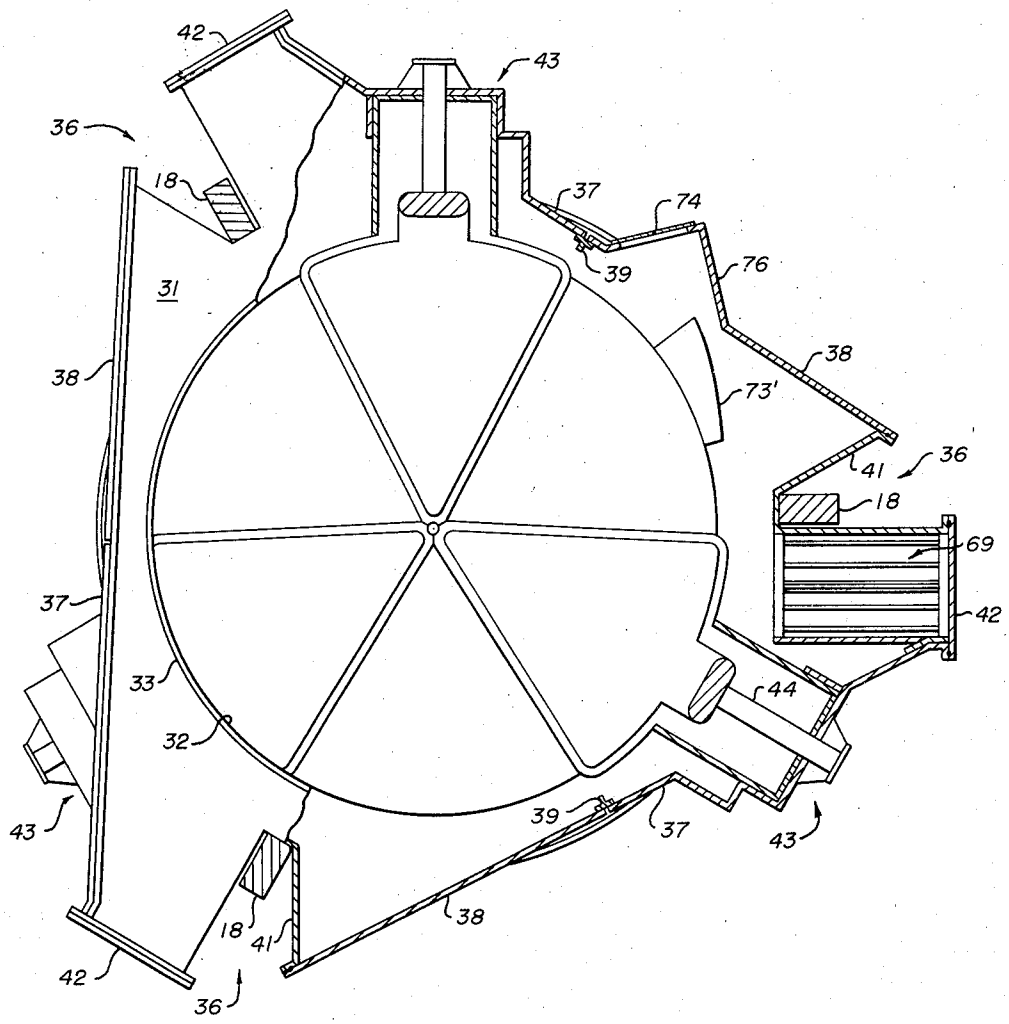


Fig. 7.

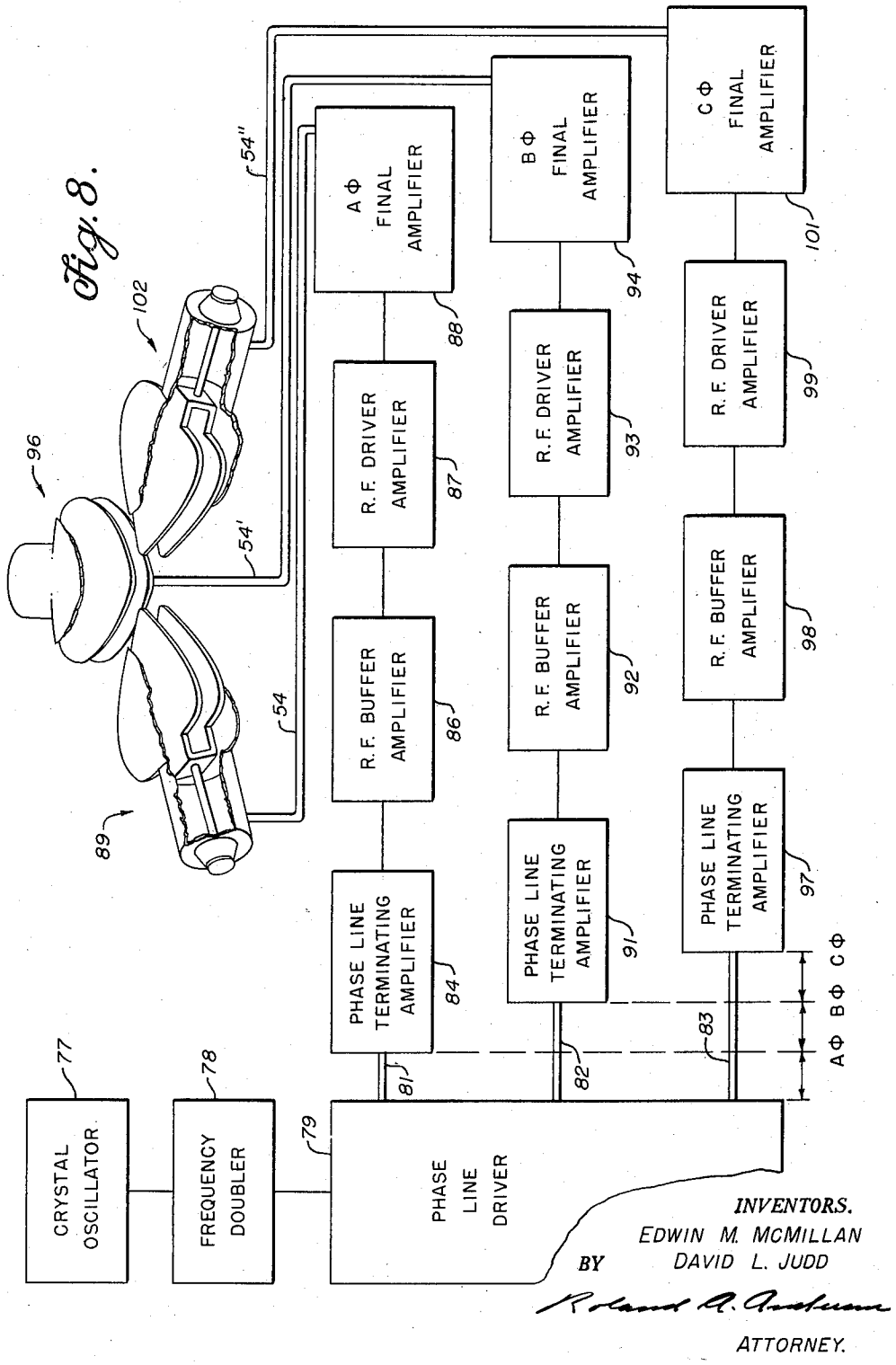
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Filed April 12, 1956 4 Sheets-Sheet 4

Fig. 8.



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CLOVERLEAF CYCLOTRON

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Application April 12, 1956, Serial No. 577,906

11 Claims. (Cl. 250—27)

The present invention relates to charged particle accelerators and more particularly to machines of the cyclotron class wherein magnetically confined particles are accelerated by repeated passage through an alternating electric field.

The basic cyclotron, as described in U. S. Patent No. 1,948,384, Method and Apparatus for the Acceleration of Ions, issued to Ernest O. Lawrence, February 20, 1934, comprises spaced apart coaxial magnetic poles and a dee electrode structure disposed therebetween. The dee structure is energized to provide an alternating electric field at right angles to the magnetic field whereby charged particles introduced near the center of the system are accelerated. Owing to the magnetic field, the particles describe a curvilinear orbit which expands as the particles gain energy by repeated passage through the electric field. A detailed description of the basic cyclotron, as well as the operating principles thereof, may be had by reference to the above-mentioned patent or by reference to the many publications available within the art.

Following the enunciation of the cyclotron principle by Lawrence in 1928, continuing efforts have been made to maximize the final energy of particle beams accelerated in such devices. It has been found, however, that certain phenomena tend to limit the attainable energy. Prominent among these is the mass increase experienced by particles at extremely high velocities. The fundamental cyclotron principle requires that the time for one revolution of a particle in the magnetic field be constant and independent of the particle energy. Thus the magnetic field, electric field, and the frequency thereof, may be held at fixed values throughout the period of particle acceleration. This requirement pre-supposes a like constancy in the mass of the particle. However, as the particles are accelerated into the relativistic range of velocities, a mass increase occurs and the particles pass out of phase with the alternating electric field, with consequent loss of the beam.

One means of overcoming the above-stated limitation is to progressively lower the frequency of the alternating electric field as a given pulse of particles is accelerated. In such manner a satisfactory phase relationship is maintained and acceleration to extremely high energy is accomplished. The foregoing method of operation is embodied in the frequency modulated synchrocyclotron and may be studied in detail by reference to U. S. Patent No. 2,615,129, Synchrocyclotron, issued to Edwin M. McMillan, October 21, 1952.

The frequency modulation system imposes a severe limitation on beam current. Machines of the latter class accelerate particles in widely separated pulses, one pulse to each frequency modulation cycle. Thus the average beam current is low in comparison with a conventional cyclotron.

A second means of compensating for relativistic mass increase of the particles is to provide a magnetic field increasing in intensity as the particles move outward

from the center of the system. Heretofore, such solution has been considered undesirable inasmuch as the stability of the particle beam is adversely affected and, as will hereinafter be described in more detail, particles accelerated in a simple field of the stated configuration exhibit axial instability, i. e., the particles experience axial repelling forces at right angles to the desired orbit and, if unchecked, strike the magnet tips or dee structure. For the foregoing reason, it has heretofore been considered necessary in a high energy cyclotron to utilize a uniform magnetic field or a magnetic field which decreases in intensity from the center outward, the latter configuration having a positive effect on the axial stability of the particle beam.

The present invention is a cyclotron embodying a unique magnetic field configuration, which configuration increases in intensity with radius and therefore compensates for the relativistic mass effect, the field having further convolutions productive of axial stability in the particle beam. By reconciling the seemingly opposed requirements of mass increase compensation on one hand and axial stability on the other, the production of extremely high current particle beams in the relativistic energy range is made feasible. Certain further advantages inhere in the invention, notably an increase in the usable magnet gap, simplified and more efficient extraction of the beam from the accelerator, and ready adaptation to the use of multiply phased excitation as contrasted with the single phased systems heretofore utilized.

It is therefore an object of the invention to provide improved means for the production of high energy charged particle beams.

It is also an object of the invention to provide a constant frequency cyclotron capable of accelerating charged particles to relativistic energies.

It is a further object of the invention to provide a cyclotron delivering a greater beam current at high energies than has heretofore been feasible.

Still another object of the present invention is to provide a constant frequency cyclotron characterized by axial stability of the particle beam and further characterized by means compensating for the phase disrupting effect of relativistic mass increase of the particles.

It is a still further object of the invention to provide means for maximizing the usable magnetic gap width in a cyclotron.

It is another important object of the invention to provide a cyclotron embodying a multiple dee structure and multiply phased radio-frequency excitation.

Still another object of the invention is to provide a cyclotron having means for the ready extraction of a large proportion of the internal particle beam.

The invention, both as to its organization and method of operation, together with further objects and advantages thereof will best be understood by reference to the following specification taken in conjunction with the accompanying drawings in which:

Figure 1, having Part A and Part B, is a radial section of two possible configurations of a circular magnet pole tip of the type customarily employed in cyclotrons, and showing the forces experienced by a charged particle circulating within the fields thereof;

Figure 2 is a perspective view of a magnet pole tip having a configuration conforming with the present invention;

Figure 3 is an elevation view of the magnet pole tip shown in Fig. 2 further clarifying the structure thereof;

Figure 4 is a cross-section view of the magnet pole tip shown in Fig. 2, taken along line 4—4 thereof;

Figure 5 is a schematic drawing of portions of the orbit described by a charged particle circulating within

the magnetic field established between pole tips as illustrated in Fig. 2;

Figure 6 is an elevational cross section of one embodiment of the invention;

Figure 7 is a plan view of the apparatus taken along line 7—7 of Fig. 6; and

Figure 8 is a block diagram of the radio-frequency excitation system of the cyclotron shown in Figs. 6 and 7.

Referring now to the drawing and more particularly to Fig. 1 thereof, there will first be discussed certain general factors relating to the behavior of charged particles in the field of opposed coaxial circular magnets of the class generally employed in cyclotrons.

In a cyclotron, particles circulate in an expanding orbit which occupies a plane at right angles to the axis of the magnet, the plane generaly being the median plane between the opposed pole tips. The particles may, under certain conditions, depart from the preferred orbit, such deviation being resolved for purposes of discussion into lateral movement within the median plane which effect is termed radial deviation, and movement at right angles to the median plane which effect is termed axial deviation. These deviations may, in certain circumstances, give rise to forces tending to increase them, resulting in loss of the particles, in which case the cyclotron is characterized as radially unstable or axially unstable.

Considering now the phenomenon of axial instability, Fig. 1A represents a magnetic field decreasing in intensity from its center outward. As may be seen by considering the convexity of the magnetic flux lines with respect to the center of such a field, a circulating particle which has deviated from the median plane will be axially stable in that it experiences a component of force directed toward the median plane. However, the weakened intensity towards the periphery of the field results in an increase in the time required for a particle to complete a revolution. This increase adds to the increase brought about by relativistic mass effects with the result that the particle rapidly passes out of phase with the alternating electric field.

Conversely Fig. 1B represents a magnetic field increasing in intensity from the axis outward. A field of such configuration compensates for the relativistic effect in that the mass increase experienced by a particle moving outward from the center of the system may be matched by a corresponding increase in the restraining magnetic field. As is seen, however, a field of this configuration is productive of axial instability in that deviant particles are subjected to a component of force directed away from the median plane.

The frequency modulated synchrocyclotron may be considered as utilizing an axially stable field configuration, Fig. 1A, with the provision of secondary means to compensate for the mass increase effect.

The present invention solves the problem by a converse technique, the utilization of what is basically a mass increase compensating field, Fig. 1B, having superimposed thereon provision to overcome the axial instability normally characteristic of such fields. Specifically, the present invention utilizes a magnetic field which both increases with radius and varies in intensity with azimuth. Referrng now to Figs. 2, 3, and 4 there is shown a magnet pole tip **11** suitable for use with the present invention. The magnet pole face contour varies in elevation with azimuth, the variation following a sinusoidal curve and increasing in amplitude outward from the center of the surface. The resultant protruding areas **12** and indented areas **13** will be termed hills and valleys, respectively.

The determination of a suitable contour or shape for the pole tip **11** depends on the establishment of a relationship defining the magnetic field at the median plane between two such pole tips coaxially spaced apart, as in a cyclotron. The principle of combined axial focusing and phase compensation embodied in this invention can be realized for a great variety of such magnetic field

relationships. In the course of the work leading to this invention and its realization, a number of general classes of such relations were invented and their properties determined. The general properties common to all the relations studied are first, an increase with increasing radius of the azimuthally averaged magnetic field and second, an azimuthal variation of field having M-fold symmetry, with M an integer greater than two, the amount of this variation increasing with increasing radius. Specific characteristics in which they differ are the wave forms of these varations with radius and azimuth. Successful operation can be achieved with any of the general classes studied. The form of field selected as an example, in constructing the cyclotron described herein, was:

$$H(r,\theta)=H_0\left[1+A\left(\frac{\omega r}{c}\right)\cos M\theta+B\left(\frac{\omega r}{c}\right)^2+C\left(\frac{\omega r}{c}\right)^3\cos M\theta+D\left(\frac{\omega r}{c}\right)^4+E\left(\frac{\omega r}{c}\right)^5\cos M\theta+F\left(\frac{\omega r}{c}\right)^6+\cdots\right]$$

where:

$H(r,\theta)$ is the magnetic field at any point in the median plane as determined by the polar coordinates r and θ,

H_0 is the field at the center of the magnet gap (the uniform field component),

ω is 2π times the frequency of circulation of particles in the magnetic field, and is a constant,

c is the free-space velocity of light,

M is the number of azimuthal maxima (hills) in the magnetic field, and

A, B, C, D, E, and F are constants which define the axial and radial focusing forces and are also adjusted to provide the phase compensation.

The series shown in the expression for the field could in principle be carried on indefinitely but sufficient accuracy for practice was obtained by calculating only the terms explicitly written. The value of the integer $M=3$ was chosen for the cyclotron described herein to simplify the pole face shaping problem to the greatest possible extent, although other larger integral values of M could be used. Some of the relationships to follow are therefore specialized to this case.

A corresponding expression for the magnetic equipotential surface required to produce the magnetic field defined above, the parameter M being fixed at three, and thus an expression for the face contour of the pole tips **11**, as used in this embodiment, is as follows:

$$\phi(r,\theta,Z)=H_0Z\left[1+B\left(\frac{\omega r}{c}\right)^2-\frac{2}{3}B\left(\frac{\omega r}{c}\right)^2+D\left\{\left(\frac{\omega r}{c}\right)^4-\frac{8}{3}\left(\frac{\omega r}{c}\right)^2\left(\frac{\omega Z}{c}\right)^2+\frac{8}{15}\left(\frac{\omega Z}{c}\right)^4\right\}+A\left(\frac{\omega r}{c}\right)\cos 3\theta\left\{1+\frac{4}{3}\left(\frac{Z}{r}\right)^2+\frac{8}{15}\left(\frac{Z}{r}\right)^4\right\}+C\left(\frac{\omega r}{c}\right)^3\cos 3\theta\right]$$

where ϕ is the magnetic scalar potential at a point defined by the radius r, the azimuthal angle θ and the distance Z from the median plane.

The above expressions define the shape of the magnet pole tips **11** to a sufficient degree of precision provided the iron in the pole tips does not saturate. In some instances, saturation effects at the periphery of the magnetic field may require modification of the pole tip contour, the necessary modification being best determined empirically for each individual embodiment of the invention. For this reason terms in ϕ arising from the small correction terms in E and F have not been included.

The constants, B, D, F, . . . are determined in terms of the constants A, C, E, . . . by the requirement that the increase in average magnetic field with radius be

appropriate to compensate for the relativistic mass increase of the accelerated particles. The constants A, C, and E, are then determinative of the degree of axial and radial focusing in the field, or in the physical sense fix the curvature of the azimuthal convolutions in the pole faces. Increasing any of these constants increases the strength of both the axial and radial restoring forces. For any cyclotron of this type there exists a maximum strength of radial restoring force above which the radial oscillations become unstable. The radial restoring force must necessarily increase with particle velocity even if the axial force is kept constant. Thus, the larger the axial restoring force is, the lower is the particle velocity at which the beam will become radially unstable. Theoretical maximum particle energy would be obtained by setting the axial restoring forces at zero, corresponding to certain minimum values of the constants A, C, E, . . . , fixed by the condition that the axial focusing forces due to the azimuthal variations must cancel the defocusing forces produced by the radially increasing magnetic field. For the present embodiment, with $M=3$, suitable values for the constants A, C, and E were found to be:

$$A=1.30$$
$$C=0.80$$
$$E=0$$

Values for the constants B and D were determined from the relationships:

$$B=\frac{1}{2}-\frac{A^2}{8}$$

and

$$D=\frac{3}{8}+\frac{9}{128}A^2-\frac{3}{8}AC+\frac{9}{2240}A^3$$

The constant F was adjusted empirically in the cyclotron herein described, about a calculated value of 0.42 obtained from a formula similar to these, which apply to the case $M=3$.

Referring now to Fig. 5, there are shown portions of the orbit of a charged particle circulating within the magnetic field described above, the particle being assumed to be circulating under the influence of a constant frequency alternating electric field. The orbit will deform from a substantially circular one 14 in the initial stages to a later configuration 14' having M curvilinear segments joined by M nodes of relatively greater curvature, the factor M in the present example being fixed at a value of three.

Since the azimuthally averaged field increases with radius, the field is one in which the mass increase of accelerated particles may be compensated for and a phase stable particle beam may be accelerated at constant frequency. This is also the condition which would normally be productive of axial instability. Considering now the mechanism by which the axial defocusing forces are overcome, it may be seen that a distortion of the symmetric field of Fig. 1B is present. Whereas in the field of Fig. 1B the magnetic flux lines are bowed directly inward toward the center of the field and produce a defocusing effect on the particle beam, a portion of the flux lines in the presently described field bow from the hills in the direction of the adjacent valleys. A charged particle tracing these portions of the orbit thus experiences a field in which the flux lines are bowed outward with respect to the particle's instantaneous center of curvature, i. e., the field as experience by the particle is loosely analogous to the field of Fig. 1A in contrast to that of Fig. 1B. This focusing effect is operative only in those sectors of the field which are intermediate between the valley and hill maxima.

At the high points of the hills and the troughs of the valleys, distortion of the magnetic flux lines is radially inward and outward, respectively. Thus, in these regions the effects of simple radially increasing or decreasing fields occur, corresponding to defocusing on hills and focusing in valleys. As described above, the azimuthally averaged field increases to provide phase compensation, so that the defocusing effect on the hills outweighs the focusing effect in the valleys. The focusing effect in the transition sections is large enough to overcompensate this net defocusing on hills and valleys with the selection of constants made above. An especially interesting fact is that the very alternation between focusing and defocusing described above produces a net focusing action which enhances the favorable focusing effect of the transition regions as described above. This constitutes an application of the theory of the Mathieu-Hill differential equation, and, more generally, of the Floquet theory of differential equations with periodic coefficients, to the problem of the stability of particle orbits in accelerators. These theories were used in detail to calculate the focusing properties discussed above.

It is important to note that the restoring of focusing forces acting to reduce an unwanted departure of a particle from its desired orbit in the radial direction arise as a combination of two aiding effects and not as a difference between a focusing and a defocusing effect as described above for vertical focusing. These two effects are first, that due to the average increase in field (which in itself produces stronger radial focusing than in a conventional cyclotron with average decrease in field with increasing radius) and second, that due to the special property of the present field (the azimuthal field variation and the noncircular orbits resulting therefrom). This second focusing effect may again be divided into two parts, one due to the outward bowing of the flux lines in transition regions between hills and valleys as described above, which tends to reduce the strength of radial focusing, and one due to the alternating gradients between focusing and defocusing on hills and valleys also described above, which also depends on the theory of differential equations with periodic coefficients as mentioned earlier.

An important property of systems governed by such equations is that loss of stability may result from too strong a focusing effect just as it may also result from a simple negative or defocusing effect. This property results in the fact that instability in the radial direction will result if the radial focusing is so strong as to produce one half wave of a full focusing oscillation within an azimuthal extent equal to that between two successive hills of the magnetic field configuration. The effect is of importance in two ways in cyclotrons utilizing the principles here disclosed. First, increasing the size of the focusing parameters A, C, etc., which increases the axial focusing force as required to counteract the axially unfavorable increase of field with radius, also results in increasing the radial focusing force leading to attainment of the radial overshoot type of instability at a lower final particle energy. Conversely, reducing these parameters postpones radial instability to a higher final particle instability but reduces the energy at which axial stability is lost. For this reason there exists an optimum choice in a restricted sense, that if a cyclotron were operable with only infinitestimal magnetic axial stability there would exist values of A, C, etc., to provide it which would be minimal and therefore would postpone the radial overshoot instability to the greatest possible final particle energy. In practice, however, a finite amount of axial focusing must be provided, its amount being a matter of judgment and experience, and in itself determining the amount by which the absolute upper limit of attainable particle energy exceeds a practically attainable value for any particular choice of field configuration such as the sinusoidal one adopted herein. The constants listed above represent a successful solution of this problem for the field configuration chosen.

The second important aspect of the radial overshoot instability is its application, on the cyclotron described

herein, to the problem of extracting the accelerated beam from the cyclotron. This is accomplished by so choosing the parameters A, C, etc., so as to produce the radial instability at the final orbit, of full energy, at the periphery of the magnetic field. On entering this region of instability, particles will possess radial oscillations, under the focusing forces described, of varying amplitudes and random phases with respect to the magnet structure. The instability is such as to sort out the phases by causing those amplitudes of one phase to fall exponentially and those of the opposite phase to grow exponentially, so that after a few turns in this region, all particles will experience the crests of their radial oscillations at the same positions on the magnet structure, the crests being further outward radially after every turn. This property enhances the ease of ejecting the accelerated particles from the magnet at a particular azimuth in a relatively well-directed beam.

A still further property of magnetic fields of the type described is important in beam extraction, even if the overshoot instability is not exploited, and serves to further differentiate such cyclotrons from conventional ones with axially symmetric fields. In conventional cyclotrons the frequency of radial oscillation is less than the frequency of circulation of particles around the magnetic field, while with fields having the properties herein described, the relationship is reversed and the radial oscillation frequency is greater. The result of this is that in a conventional cyclotron a local region of depressed or weakened magnetic field at the periphery of the magnet does not attract the high energy beam toward itself to facilitate beam extraction, but, on the contrary, repels it, while in the fields described the opposite occurs, a locally weak region attracting the beam so as to make the process continue in that the beam will continue to drift in the desired direction into an ever decreasing field from which it can be made to emerge from the magnet. All of the focusing properties described above have been verified to exist on the cyclotron herein described.

Considering the adaptation of the described magnetic field to use in a cyclotron, it will be found that the accelerating electrodes or dees, providing the electric field, will be most conveniently disposed in the valley sectors of the magnet in order to maximize the gap available for the particle beam. Since the number of valleys (M) may equal or exceed three, the cyclotron is adaptable to the use of a multiple dee system in contrast to the one or two dee systems heretofore employed. Thus a number of accelerating electrodes equal to the value M may be conveniently used, one inserted in each valley sector of the magnet gap. Excitation may then be provided with an $2\pi/M$ phase angle between adjacent electrodes. It will be appreciated that less than M dees may be satisfactorily employed, for example, a single dee inserted in one valley sector might be used. Similarly, various alternative phase relationships will be found workable in a multiple dee system, for example, all dees may be excited at a single phase having a frequency equal to M divided by the period of orbital revolution of particles within the field.

Referring now to Figs. 6 and 7, there is shown a cyclotron utilizing the described magnetic field and embodying certain novel components adapted for use therewith.

Two right cylindrical coaxial magnet poles, an upper pole 16 and lower pole 16' are spaced apart along a vertical axis, the lower pole 16' resting upon a suitable concrete foundation 17. Heavy stanchions 18 are spaced around the periphery of the magnet structure supporting the upper pole piece 16. To provide excitation for the magnet, a multi-turn winding is disposed coaxially about each pole piece, an upper coil 19 being disposed in an annular step 21 at the lower extremity of the upper pole piece 16, and a lower coil 19' being disposed in a similar annular step 21' in the upper extremity of the lower pole piece 16'.

An upper pole tip 22, having the lower face contoured in accordance with the previously given expressions, is secured in a coaxial manner to the lower extremity of the upper pole piece 16, the pole tip being fastened by heavy bolts 23 which pass through vertical bores 24 in the pole piece and engage threaded bores 26 in the upper extremity of the pole tip. A lower pole tip 22' of similar configuration is mounted on the upper face of the lower pole piece 16' by bolts 23'. It will be observed that the hill sections 27 of the upper pole tip 22 are positioned directly above the hill sections 27' of the lower pole tip 22' in order to produce the desired magnetic field, the two pole tips being separated by a gap 28 through which particles may be accelerated.

Provision for the maintenance of a vacuum in the particle accelerating region comprises a tank 29 surrounding the central portion of the magnet structure and sealing the gap 28 from external atmosphere. The tank 29, in this embodiment, is constructed in a generally triangular plan and, in detail, comprises a triangular top plate 31 having a circular central opening 32 through which the upper magnet pole tip 22 passes. The central opening 32 is provided with an upwardly projecting rim 33 fitting tightly against the pole tip 22, suitable vacuum sealing means 34 being disposed in the juncture. As best shown in Fig. 7, the tank 29, and thus the top plate 31, are truncated at the apices which are utilized as vacuum manifolding as will hereinafter be described. Similarly, the top plate 31 is indented at suitable points 36 to provide for the passage of the upper magnet supporting stanchions 18.

A lower vacuum tank plate 31', similar in configuration and alignment to the top plate 31, is disposed surrounding the lower pole tip 22', the lower plate being provided with a central opening 32' having a downwardly projecting rim 33' which sealingly fits against the lower pole tip. Each lateral face of the tank 29 is formed by two adjoining plate sections 37 and 38, vertical posts 39 being disposed between the upper plate 31 and lower plate 31' to provide bearing surfaces for sealing the junctures of the two plate sections. Angled side plates 41 extend between the upper plate 31 and lower plate 31' at the stanchion accommodating indentations 36. Similarly, plates 42 close the truncated apices of the triangular tank 29. It will be appreciated that all junctures between the various plates forming the tank 29 must be made vacuum tight as by suitable gaskets or by brazed joints.

The first plate sections 37 are positioned at the azimuthal portions of the magnet corresponding to the valleys and each is provided with an oblique outwardly projecting tubulation 43, the axis of the tubulation being colinear with the centerline of the valley.

An elongated cylindrical dee electrode stem 44 is disposed within each tubulation 43 and aligned along the centerline of the adjacent magnet valley, one extremity of the dee stem being transpierced through an aperture in the extremity of the tubulation and being rigidly secured thereto by a suitable bracket 46. The dee electrodes each comprises two spaced parallel, substantially triangular conducting plates 47 disposed in the valley sectors of the magnet gap 28, one above and one below the median plane of the gap. Each set of dee plates 47 is mounted by means of a conducting yoke 50 to the innermost extremity of a dee stem 44.

To utilize the dee structure 47 as a resonant transmission line, thus facilitating the transfer of radio-frequency excitation thereto, and to properly shape the resultant electric field in the particle accelerating region of the magnet gap, a conducting dee liner 48 is disposed surrounding the major portion of the dee stem 44 and dee electrodes 47. Each liner 48 includes a cylindrical section 49 disposed within the tubulation 43 coaxial with the dee stem 44, an adjoining tapered transition section 51, and two dished triangular plate sections 52 disposed one above and one below the dee plates 47. The liner

plate sections 52 are spaced from the dee plate sections 47 and are curved at the edges to bring the edges into the planes of the dee plates in such a manner that the electric field lines between the edges of the dee plates and the edges of the liner plates will be substantially horizontal. In order that the dee stem 44, dee plates 47, and liner 48 will effectively form a coaxial resonator, all joints between the component pieces must be made electrically conductive. In the present embodiment the system resonates as a one quarter wave line closed at one extremity, the closure being made by an annular conducting plate 53 coaxially disposed between the dee stem 44 and cylindrical section 49 of the liner 48 adjacent the extremity of tubulation 43.

Delivery of radio-frequency excitation to the dees is effected by a coaxial conductor 54 which terminates at an aperture 56 in the tubulation 43. The center conductor 57 of the coaxial conductor 54 projects into the interior cavity of the liner 48 and connects with one end of a coupling loop 58, the opposite end of the loop being electrically connected with the adjacent wall of the liner. For proper transfer of energy to the resonant system, the loop 58 must lie in a plane which is parallel to the dee stem 44. The coaxial conductor 54 is excited by oscillator means which will hereinafter be described.

Considering now provision for the introduction of charged particles into the accelerating region of the magnet gap 28, it will be appreciated that any of the varieties of particles customarily accelerated in cyclotrons may be accelerated in the present invention, for example, protons, deuterons, or electrons may be readily accelerated. Similarly, the ion source utilized in the present invention may be of conventional design, preferably of a design emitting high particle current to realize the beam current potentialities of the present invention. It will be found preferable to dispose the source 59 at the lower extremity of an elongated probe 61 which is inserted through an axial bore 62 in the upper pole 16 and upper pole face 22. The upper extremity of the probe 61 is provided with a flange 63 which bears against a corresponding flange 64 of a cylindrical insert 66 which lines the upper portion of the bore 62, an annular sealing element 67 being disposed between the two flanges. The ion source 59 should be positioned in such a manner that ions are emitted in the median plane between the opposed pole faces and with a component of motion in the median plane.

To evacuate atmosphere from the particle accelerating region of the magnet gap 28, diffusion vacuum pumps 68 are secured to the underside of the vacuum tank 29, at the apices thereof, the inlets of the pumps being opened to the interior of the tank. As is well understood in the art, the diffusion pumps 68 should be connected to suitable mechanical roughing pumps which exhaust to the atmosphere. To prevent the passage of vapors into the interior of the vacuum tank, a refrigerated baffle 69 is disposed in each apex of the tank. The baffles 69 in this embodiment take the form of a gridwork of coolant conduits 71 disposed obliquely within the lower corner of each apex of the vacuum tank 29, the gridwork having vertical triangular side portions 72 whereby the assembly covers the passage between the magnet gap 28 and the inlet to the vacuum pumps 68. A refrigerant such as liquid nitrogen is circulated through the conduits 71 to provide the desired low temperature.

As will hereinafter be described in more detail, particles emanating from the source 59 circulate about the axis of the magnet gap 28 in an orbit which expands in radius, the particles gaining energy by repeated passage through the electric field which exists between the dees 47 and dee liners 48. Upon reaching the periphery of the magnet gap 28, in the absence of auxiliary extractor means, the particles will be found to emerge in a generally tangential direction with respect to the magnet structure. The azimuthal distribution of the emergent particles will normally be found to be uneven, the emergent particles being somewhat concentrated at the azimuths corresponding to the hill sectors of the magnet.

In many instances it will be more desirable to focus the emergent particles into one or more well-defined beams. It will be found that the particles may be made to emerge preferentially from a particular hill by weakening the field at the outer terminus of the hill. A similar effect may be achieved by strengthening the field at the outer terminus of the diametrically opposed valley. The two effects may be used jointly or singly to produce a semi-focused beam from one or more of the magnet hills. It will be apparent that conventional beam focusing lenses, solenoid lenses, or quadripole alternating gradient lenses for example, may be utilized to further focus the particles which have been removed from the magnet gap.

Means by which the desired alterations in the magnetic field may be accomplished include the addition of peripherally mounted ferromagnetic shims at the hill points where it is desired to spread the magnetic flux and thus weaken the field, and the addition of internally mounted shims at the valley points where it is desired to concentrate flux and thus strengthen the field. It will be apparent that auxiliary windings might be mounted on the pole faces to effect the desired alterations in the field. Similarly, various forms of magnetic channel might be employed to divert the beam at a particular azimuth.

In the present embodiment the particle extraction means comprises a magnetic shim formed by two spaced ferromagnetic blocks 73 and 73', the first block 73 being secured to the periphery of the upper magnet tip 22 substantially at the centerline of a hill sector and the second block 73' being secured to the periphery of the lower magnet tip 22' at a similar azimuth. The effect of the blocks 73 and 73' is to distribute the local magnetic flux over a wider area and thus create a region of weakened field. Circulating particles encountering the weakened region will seek an orbit of greater radius and by thus moving outward will be enabled to escape from the magnetic field, the action being aided by the considerations relative to radial instability as hereinbefore discussed. To minimize beam loss at the point where the beam passes through the wall of the vacuum tank 29, a thin window 74 is disposed in the wall, the wall being provided with an angled section 76 in order that the window may be oriented at right angles to the beam.

Referring now to Fig. 8, there will be described means for supplying radio-frequency excitation to the dee structures. A crystal oscillator 77, resonant at one half the cyclotron operating frequency, delivers a signal to a frequency doubler 78. It will be apparent that the oscillator 77 could be selected to operate at the cyclotron frequency eliminating the need for the frequency doubler 78; however, signal strength and stability are more easily maximized in a lower frequency oscillator. The output of the frequency doubler 78 is connected to the input of a phase line driving amplifier 79 which drives three independent delay lines 81, 82, and 83. The delay lines 81, 82, and 83 serve to separate the original signal into three signals differing in phase by 120 degrees in order that the three dees of the cyclotron may be excited in a corresponding manner.

The first or A phase delay line 81 is terminated in an amplifier 84 which is series connected with three further stages of amplification, an isolating or buffer amplifier 86, a driver amplifier 87, and a final or power amplifier 88. Excitation from the final amplifier 88 is transmitted through coaxial line 54 to the dee assembly 89. Similarly the B phase delay line 82 connects through a terminating amplifier 91, buffer amplifier 92, driver amplifier 93, and final amplifier 94 to a coaxial line 54' which delivers excitation to the second dee assembly 96. The C phase delay line 83 is similarly connected through terminating

amplifier 97, buffer amplifier 98, driver amplifier 99, final amplifier 101, and coaxial line 54'' to the third dee assembly 102. It will be apparent that with proper selection of components the above system is susceptible to servo operated phase and voltage controls should such be desired.

In operation, magnet coils 19 and 19' are energized from a suitable source of stabilized direct current, setting up a field in the magnet gap 23 having a configuration corresponding to the previously given expressions. The dee resonator assemblies are excited by the oscillator-amplifier system to produce alternating electric fields between the dees 47 and dee liners 48. Source 59 is energized to emit ions into the magnet gap 28, the gap being continually evacuated by the action of the diffusion pumps 68. The ions, encountering the electric fields within the dee structures, will be accelerated, the resultant ion trajectory being curvilinear about the axis of the magnet owing to the presence of the magnetic field at right angles to the electric field. With each traversal across the gap between a dee 47 and dee liner 48, the increment of energy will be imparted to the ions resulting in an increase in the averaged radius of the ion orbit. As has been described, the ion orbit will depart increasingly from a circular one as the averaged radius increases owing to the convolutions in the magnetic field introduced by the hill and valley sectors of the magnet. The deviation so introduced will compensate for the increasing mass of the ions with the result that the period of revolution of the ions in the cyclotron will be constant at all radii.

Upon reaching the periphery of the magnet gap 28, the weakened field brought about by extractor shims 73 and 73' causes the ions to depart entirely from the accelerator through the tank window 74. The beam so produced may be focused and utilized in any of the well-known applications to which high energy particle beams are adaptable.

While the invention has been disclosed with respect to a single embodiment, it will be apparent to those skilled in the art that numerous variations and modifications may be made within the spirit and scope of the invention and thus it is not intended to limit the invention except as defined in the following claims.

What is claimed is:

1. In a cyclotron the combination comprising coaxial cylindrical magnet poles spaced apart to form a magnet gap, the proximal faces of said magnet poles having a nonplanar contour characterized by depressed sectors alternated with elevated sectors, the magnitude of said depressions and elevations increasing with radius, vacuum wall means sealing said magnet gap from external atmosphere, a source unit emitting charged particles into said magnet gap, at least one dee electrode disposed between said magnet poles at an azimuthal position corresponding to one of the depressed sectors of said magnet pole faces, and electrical oscillator means energizing said dee electrode to produce an alternating electric field within said magnet gap.

2. A cyclotron substantially as described in claim 1 and further characterized by means producing a variation in intensity of the magnetic field in at least one region on the periphery of said magnet gap whereby particles circulating within the field of said poles are caused to emerge from said magnetic field.

3. A cyclotron comprising, in combination, two spaced coaxial cylindrical magnet poles each having a nonplanar pole face characterized by axially projected sectors alternated with axially recessed sectors, said projected sectors and recessed sectors being formed by sinusoidal undulations along the azimuth of said pole faces, said sinusoidal undulations being of continually greater amplitude towards the periphery of said magnet pole faces, a vacuum barrier shielding the region between said poles from external atmosphere, a plurality of wedge shaped dee electrodes disposed between said magnet poles at azimuthal positions corresponding to the axially recessed sectors thereof, each of said dee electrodes having a continuous particle passage in the region of the median plane between said magnet poles, oscillator means supplying excitation to each of said plurality of dee electrodes, means controlling the relative phase of the excitation supplied to each of said dee electrodes, and a source unit emitting charged particles substantially at the center of the gap between said magnet poles.

4. A cyclotron substantially as described in claim 3 and further characterized by particle extraction means comprising a block of ferromagnetic material disposed on each pole face of said magnet poles adjacent the periphery thereof whereby particles are caused to emerge from between said magnet poles at a particular azimuth thereof.

5. In a cyclotron the combination comprising two coaxial cylindrical magnet poles spaced apart to form a magnet gap, the faces of said magnet poles having an azimuthally undulated contour forming a magnetic field at the median plane of said magnet gap which field is characterized by M maxima located along radii separated by substantially $2\pi/M$ radians of azimuth and M field minima separated by a similar azimuthal angle, where the factor M is an integer greater than two, said field maxima being alternated with said field minima, said field maxima and said field minima being of progressively greater magnitude outward along said radii, at least one triangular dee electrode disposed between said magnet poles, the bisector of said dee electrode being aligned with the radii corresponding to one of said field minima, said dee electrode having an open particle passage at the median plane of said magnet gap, oscillator means supplying excitation to said dee electrode, vacuum barrier means sealing said magnet gap from the external atmosphere, and an ion source emitting particles substantially at the center of said magnet gap.

6. A cyclotron substantially as described in claim 5 wherein the factor M has a value equal to three and said dee electrodes are three in number.

7. A cyclotron substantially as described in claim 5 wherein said magnetic field is further characterized by a localized variation in intensity in at least one region adjacent the periphery of said field whereby the extraction of circulating particles therefrom is facilitated.

8. In a cyclotron the combination comprising two coaxial cylindrical magnet poles of dissimilar polarity, said poles being separated to define a magnet gap, the faces of said pole pieces having an azimuthally undulated contour forming three ridges aligned along radii separated by substantially $2/3\pi$ radius of azimuth alternated with three valleys aligned along radii separated by a similar azimuthal angle, the amplitude of said azimuthal undulations giving rise to said hills and said valleys being of progressively greater magnitude outward from the centers of said pole pieces, at least one wedge shaped dee electrode disposed in one of said valleys and directed along the centerline thereof, said dee electrode being formed of two triangular plates spaced one above and one below the median plane of said magnet gap, said dee electrode being one terminus of the center conductor of a two conductor resonator, the outer conductor of said resonator being comprised of dee liners projected into said magnet gap one proximal to each major face of said dee electrode, at least one electrical oscillator energizing said resonator to produce an alternating electric field between said dee electrode and said dee liner, a gas-tight vacuum wall enclosing said magnet gap, and a charged particle source emitting particles at the center of said gap.

9. In a cyclotron, as described in claim 8 wherein said dee electrodes and attendant resonators are three in number, one of said dee electrodes being disposed in each of said valleys, the further combination comprising a phase regulating circuit fixing the energization supplied each one of said resonators at a predetermined phase with

respect to the energization supplied each other of said resonators.

10. In a cyclotron as described in claim 8 wherein said dee electrodes and attendant resonators are three in number, one of said dee electrodes being disposed in each of said valleys, the further combination of circuitry phasing the energization supplied each said resonator substantially 120 electrical degrees apart from the energization supplied each other of said resonators.

11. In a cyclotron substantially as described in claim 8, the further combination of two blocks of ferromagnetic material one secured to each of said pole pieces adjacent the periphery thereof and at a common azimuth.

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