Nov. 5, 1957 L. C. TENG ET AL 2,812,463

MAGNETIC REGENERATIVE DEFLECTOR FOR CYCLOTRONS

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FIG. 1

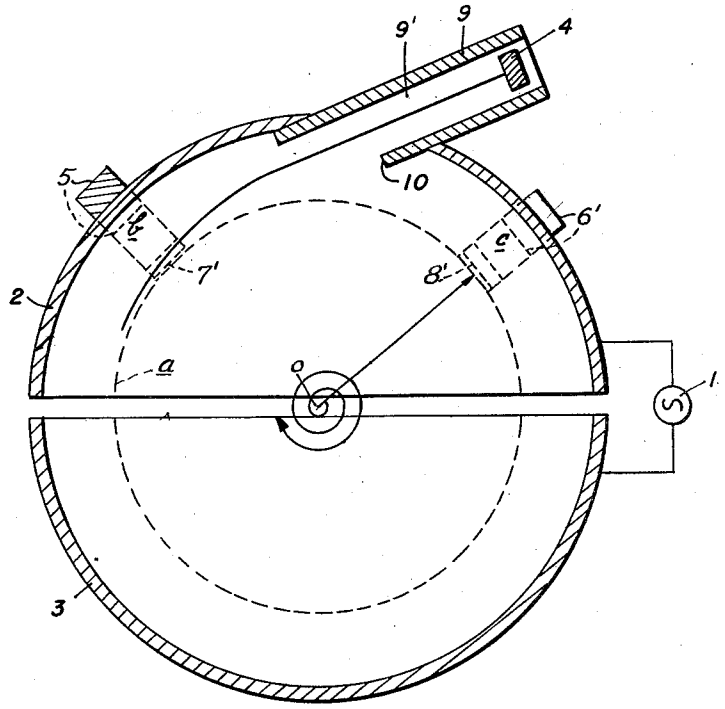
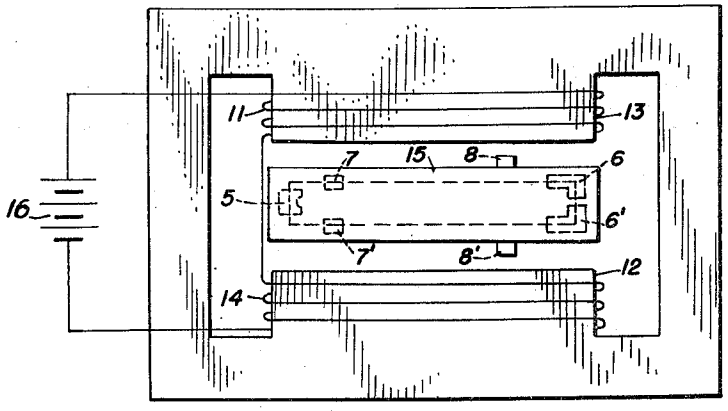


FIG. 2



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MAGNETIC REGENERATIVE DEFLECTOR FOR CYCLOTRONS

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FIG. 3

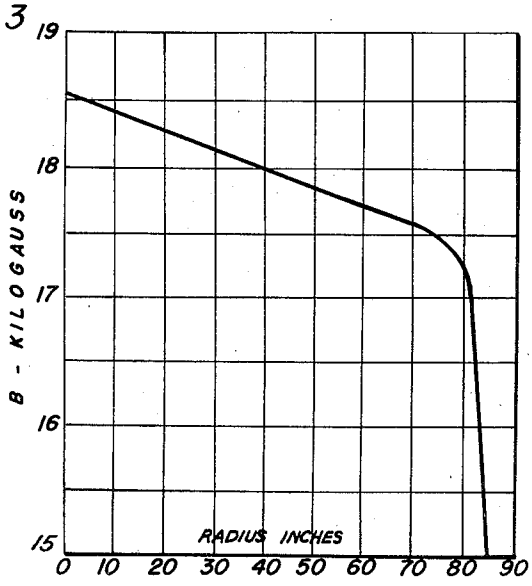


FIG. 4

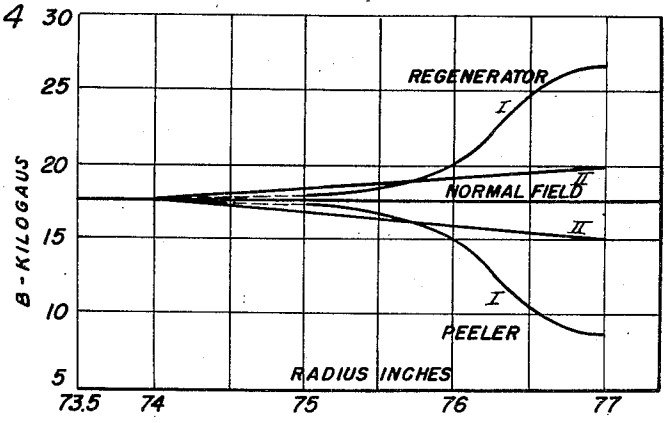
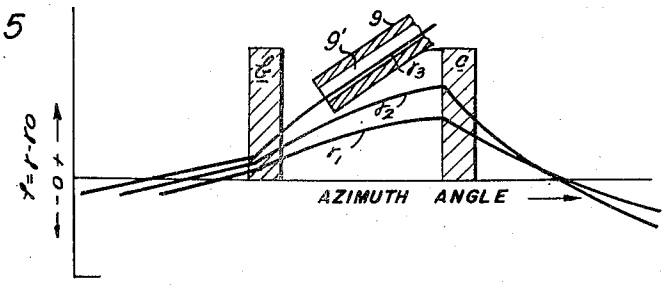


FIG. 5



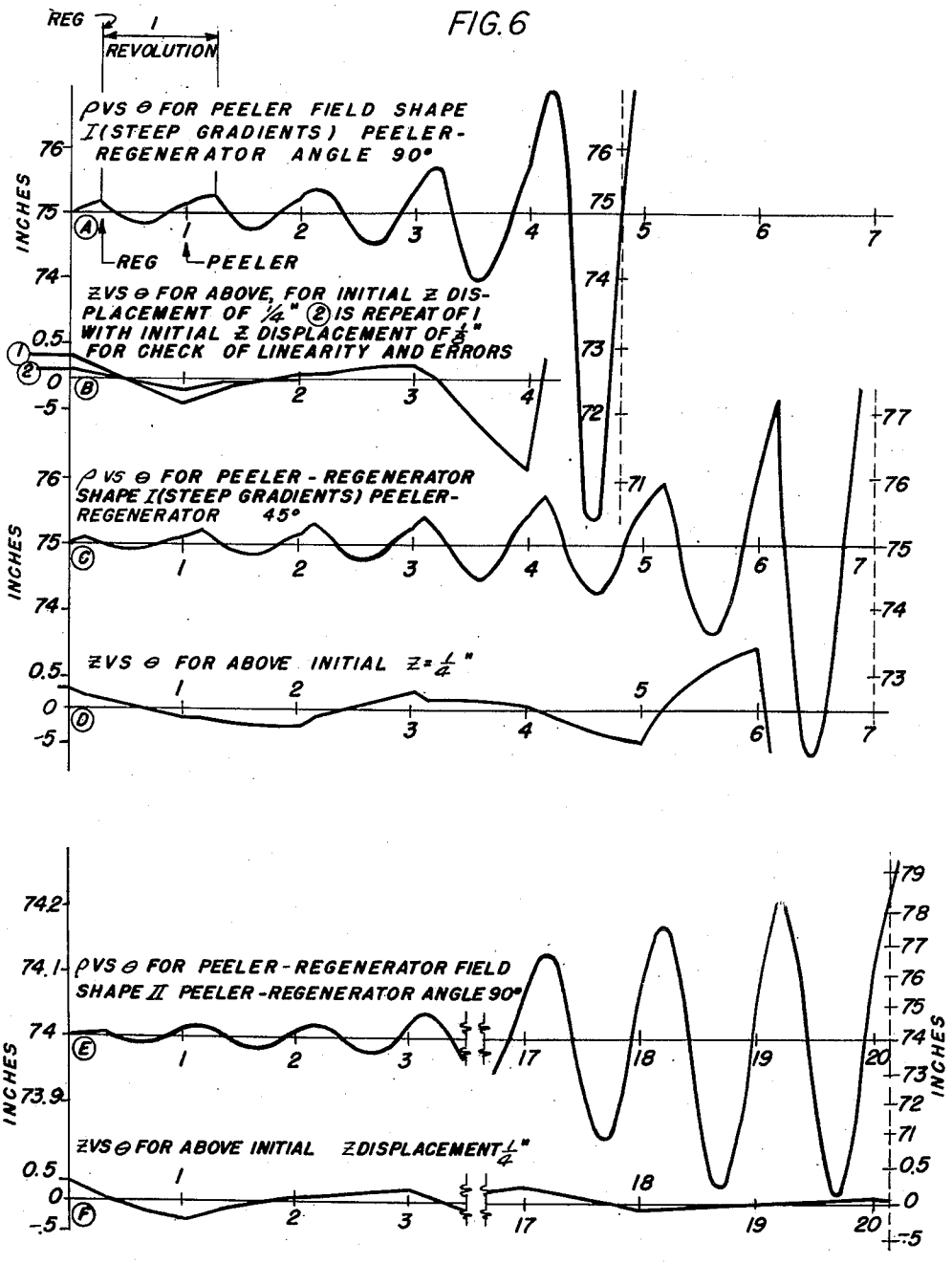
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MAGNETIC REGENERATIVE DEFLECTOR FOR CYCLOTRONS

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FIG. 6



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MAGNETIC REGENERATIVE DEFLECTOR FOR CYCLOTRONS

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FIG. 7

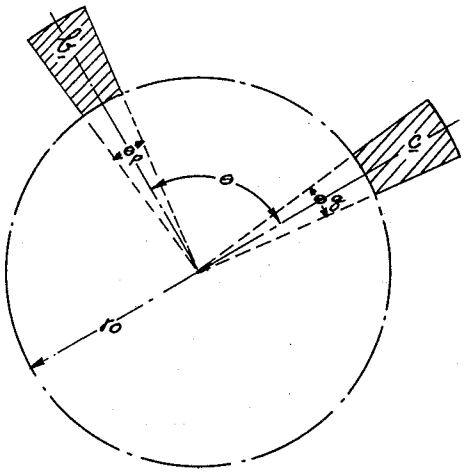


FIG. 8

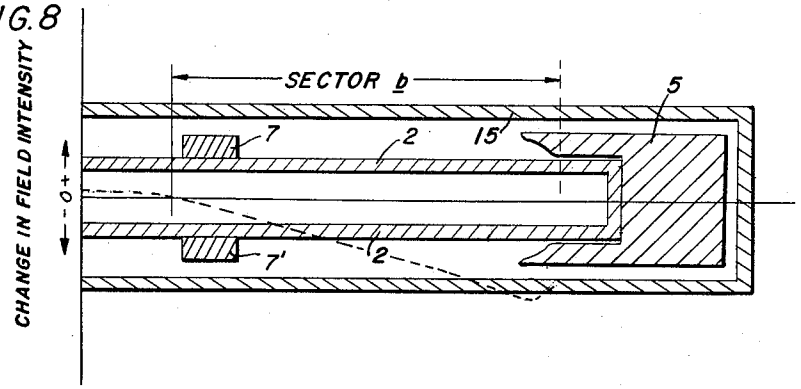
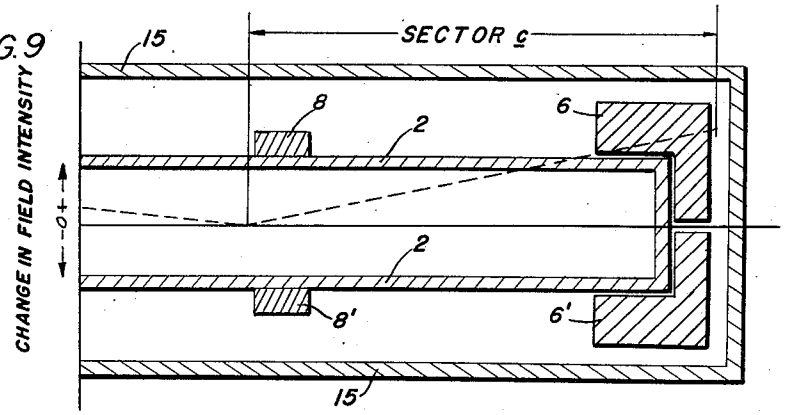


FIG. 9



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2,812,463

MAGNETIC REGENERATIVE DEFLECTOR FOR CYCLOTRONS

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Application October 5, 1951, Serial No. 249,892

7 Claims. (Cl. 313—62)

The invention relates to a novel method and apparatus for extracting accelerated particles from inside cyclotrons and the like.

More specifically, the invention relates to a novel method and apparatus for deflecting an accelerated particle following a generally circular or spiral path from its normal path by magnetic means for purposes of directing the particle at a target.

As is well known in the art, the cyclotron is a device for accelerating charged particles to high speeds by means of an alternating electric field extending between two separated electrodes and a magnetic field at right angles to the electric field, the particles being so influenced by the two fields that the particles are caused to move in a generally spiral orbit outward from a center point.

For low energy cyclotrons, the problem of extracting the accelerated particles from within the device has not posed many serious problems and numerous methods have been worked out which have been found satisfactory.

With the advent of cyclotrons capable of accelerating particles to energy levels on the order of hundreds of millions of electron volts, the high speed of the particles and the exceedingly small distances between adjacent revolutions of the spiral path present very difficult particle-extraction problems which heretofore have not been satisfactorily solved. The synchrocyclotron or frequency-modulated cyclotron has been the type of cyclotron used at these high energy levels.

One method now used to extract particles from a synchrocyclotron is the electrostatic pulsed deflection method which deflects the particles by a very strong pulsed electrostatic field. This pulse must be applied and take effect in less time than it takes a particle to make one revolution. This requires an electrostatic pulse of several hundred kilovolts with a rise time of a fraction of a micro-second which is extremely difficult to generate. With this method a maximum efficiency of only about 5 percent has been obtained.

Another method of particle extraction is the nuclear scattering deflection method where the energy of the ion beam of a cyclotron is "scattered" out of the cyclotron by causing it to first hit a target made of a material having a high atomic weight. The efficiency of this method is exceedingly low, being in the neighborhood of 0.1 of one percent and it also suffers from the disadvantage that the scattered beam has a wide energy spread.

The invention results in a tremendous improvement in efficiency by providing an extraction efficiency as much as 10 to 20 times the efficiency of the most efficient presently used deflecting systems.

The invention broadly comprises a peeler which reduces the normal orbit-controlling magnetic field to a constant weakened condition in a narrow azimuthal sector located adjacent the outer periphery of the spiral path and azimuthally beyond the channel mouth. The particle orbit is thereby caused to oscillate radially, and the amplitude of oscillation grows exponentially with successive revolutions of the particle so that after several such revolutions

the particle enters the mouth of the channel and is conducted thereby out of the magnetic field and toward the target. The amplitude in the axial direction of the magnetic field remains almost constant during this process.

An object of the invention is to provide a highly efficient particle extraction system for synchrocyclotrons and the like where the particles are given radial oscillations with rapidly increasing amplitudes with respect to their equilibrium orbits.

The exact nature of this invention as well as other objects and advantages thereof will be readily apparent from consideration of the specification to follow in connection with the annexed drawings, wherein:

Fig. 1 is a top cross-sectional view of part of a two-D cyclotron showing the positions of the modified magnetic field sectors forming a part of the invention;

Fig. 2 is an elevational view of the cyclotron apparatus forming the invention;

Fig. 3 is a curve showing one example of the normal orbit controlling magnetic field used in the specific exemplary embodiment of the invention;

Fig. 4 shows several modifications of a portion of the magnetic field distribution illustrated in Fig. 3 in the peeler and regenerator sectors shown in Fig. 1;

Fig. 5 shows a rectangular coordinate plot of the path of the particles in the area where the extraction process takes place, and the preferred location of the magnetically shielded extraction channel shown in Fig. 1;

Fig. 6 shows the path of the accelerated particles for the field conditions shown in Fig. 4 in an extended rectangular coordinate plot;

Fig. 7 shows the various angles and distances needed to mathematically explain a generic aspect of the invention; and

Figs. 8 and 9 show generally and diagrammatically the respective configurations of the peeler and regenerator forming one exemplary embodiment of the invention and also a rough graph of the effects thereof.

Referring now to the drawings, there is shown in Fig. 1 a top cross-sectional view of the inside of the electrodes (D's) of a two-D type synchrocyclotron incorporating features of the invention. An alternating voltage source 1 is connected between two spaced hollow D's 2 and 3 to provide an alternating electric field therebetween. The charged particles to be accelerated, such as proton particles, are injected by well known means into the center portion of the synchrocyclotron. A conventional magnetic field generating apparatus provides a fixed magnetic field distribution, as shown in Fig. 3, cooperating with the alternating electric field to cause the accelerated particles to travel in a spiral path which emanates from the point O. The abscissa of Fig. 3 represents the radial distance from the center portion O of the inter-electrode space and the ordinate represents the magnetic field intensity. The magnetic field bends the path of the particles, and, as they are accelerated by the alternating electric field in the space between the electrodes 2 and 3, the particles are caused to move in a spiral path as shown in Fig. 1.

A target, for example the element 4, to be bombarded by the accelerated particles is located outside of the cyclotron D's 2 and 3. An outward extending cylindrical tube 9 forms a passageway 9′ between the inside of the synchrocyclotron and the target. The accelerated particles are caused to sharply deviate from the outermost revolution *a* of the normal spiral path or orbit diagrammatically shown in Fig. 1 and to be led out of the orbit-controlling magnetic field and into the tube 9 by the novel particle extracting system comprising the invention. The cylindrical tube 9 is made of a magnetic material so that the passageway 9′ therein is free of magnetic flux and thus little or no bending of the particle path occurs therein.

The distance between adjacent revolutions of the spiral

path is exceedingly small, so that, if adequate means were not provided to suddenly deflect the particles from the normal essentially gradually expanding spiral path, the particles would strike the lip **10** at the mouth of the passageway **9'**.

As previously stated, the invention comprises modifying the field intensity of small sectors of the normal magnetic field to provide one sector *b* of reduced field intensity and another sector *c*, of increased field intensity, spaced azimuthally from the first sector. The sector *b* is called the peeler sector, and the sector *c* is called the regenerator sector.

Referring now to Fig. 2, the spiral-producing magnetic field apparatus of cyclotron accelerators generally includes a laminated magnetic core structure including windings **11** and **14** respectively wound about upper and lower pole faces **13** and **12**, and a source of direct current **16** connected in series with the windings.

The synchrocyclotron electrodes **2** and **3** are located between the pole faces **12** and **13**, and within an evacuated chamber **15**.

The magnetomotive force of the current-carrying windings **11** and **14** and the tapered pole faces **13** and **12** produce a magnetic field distribution which, in the absence of other influences, is identical at all azimuthal positions at any given radius as exemplified by the field distribution indicated by Fig. 3.

An exemplary apparatus for producing the decreasing field at the peeler sector *b* comprises an iron shim **5** located about the periphery of the **D 2** and symmetrical to the median plane thereof, and a pair of iron shims **7** and **7'** located radially inward from the shim **5** and above and below the **D**, all of said shims together constituting the peeler accounting for the flux density curve shown diagrammatically in Fig. 8, which will be hereinafter described.

The exemplary apparatus for producing an increasing magnetic field in the regenerator sector *c* comprises a pair of iron shims **6** and **6'** located respectively above and below the **D 2** and a pair of iron shims **8** and **8'** spaced radially inward from the shims **6** and **6'** and located respectively above and below the **D**, all of said shims together constituting the regenerator. Fig. 9, which will be described in more detail later, shows the flux density curve due to the regenerator.

Without the peeler and regenerator of the invention, as previously stated, the change of radial position of the particle at any given azimuthal position in the synchrocyclotron on successive revolutions in the region approaching the place of extraction would be very small and the accelerated particles would strike the lip **10**. The system forming the invention provides a particle path characterized by a sharply increasing radially outward deviation for each of successive revolutions of the particle as shown in Fig. 5 in the region approaching the place of extraction. In Fig. 5, r_1, r_2 and r_3 represent diagrammatically corresponding portions of the path of a particle at the last few successive revolutions thereof in accordance with the invention. The distance between particle path portions r_2 and r_3 is substantially greater than the thickness of the tube **9** so that the particle does not strike the lip **10**.

The normal magnetic field of particle acceleration is commonly described in terms of a parameter *n* which expresses the radial variation of the field in the form $B \approx r^{-n}$ where B is the magnetic field intensity at a distance *r* from the center O (Fig. 1) of the magnetic field. In terms of the magnetic field intensity and its derivative, the value of *n* at any radius in a magnet is given by

$$n = \frac{-r}{B}\frac{dB}{dr}$$

Knowing *n*, one may compute the frequencies of radial and axial oscillation of the particles in the beam in terms of the angular frequency of the particles around the axis of the magnet. For a synchrocyclotron, the value *n* is usually on the order of .05 in the region where the particles are about to be extracted. Toward the outer periphery of the field, *n* increases rapidly.

The first mention of a magnetic peeler for use in extraction of particles seems to have been in connection with betatrons. The problem of particle extraction in present betatrons and cyclotrons is one of rapidly increasing the radius of the particle orbit since the target is located outside the peripheral portions of such accelerators. The magnetic peeler or field-weakening method is satisfactory where the average parameter *n* of the magnetic field encountered by a particle in a single revolution is greater than .75. In the betatron *n* is greater than a .75, so that a magnetic peeler is a satisfactory extraction device.

In the area where particle extraction is to take place in the synchrocyclotron, however, *n* is less than .75 and the use of a magnetic peeler alone is unsatifscatory. It can be shown that where *n* is less than .75 a peeler device will actually cause no outward displacement of the accelerated particles.

Although it is the object of the invention to provide a sharply increasing radial displacement of the particles for extraction purposes, it would be undesirable to have the vertical displacement of the particles increase since the particles would then strike the upper or lower wall portions of the accelerating chamber formed by the **D**'s **2** and **3**, which would obviously result in a very low efficiency.

Fig. 4 shows examples of various field distributions in the peeler and regenerator sectors where each of the peeler and regenerator fields were assumed to extend through eight inches azimuthally at the radial positions there shown.

In Fig. 6, the curves A and B show respectively the radial ρ (horizontal) and axial Z (vertical) displacement with angular position of the particle where the peeler and regenerator are 90° apart and the peeler and regenerator magnetic field distributions respectively follow the curves I in Fig. 4.

The curves C and D of Fig. 6 show information similar to that of the curves A and B but with the peeler and regenerator 45° apart.

The curves E and F of Fig. 6 show information similar to that of the curves A and B but with the field distributions caused by the regenerator and peeler following the curves II of Fig. 4, the peeler and regenerator being 90° apart.

Although the conditions represented by the curves A and B of Fig. 6 indicate a very good radial displacement build-up, the vertical oscillation builds up too quickly and many particles would hit the top or bottom of the **D** structure.

The conditions represented by the curves E and F produce relatively slow vertical displacement build-up, although it takes more revolutions to produce a great enough radial displacement to cause the particles to enter the passageway **9'**. It will be noted that the curves II of Fig. 4 producing the desirable result indicated by the curves E and F are substantially linear.

One of the important features of the invention is that it produces an inherent phase stability by positioning successive particles in substantially the same axial and azimuthal position, although the particles initially entered different points in the peeler and regenerator sectors. For example, a particle which first enters the peeler sector *b* at a radial displacement of 75 inches will eventually have the same displacement as a particle entering the regenerator sector *c* at a radius of 75 inches. If this were not true, many particles would not pass into the passageway **9'**, resulting in low efficiency.

It should be apparent that the design details of a specific embodiment vary with many parameters such as the peeler and regenerator field distribution, the angle between the peeler and regenerator, etc. For this reason the paragraphs to follow outline mathematically a general solution

to the problem, taking into account the various variable parameters.

Refer to Fig. 7 where: r, z, θ are the usual cylindrical coordinates; z-axis being the axis of the magnetic field.

The magnetic field in a synchrocyclotron is defined by:

$$H_x=H_y=0,\ H_z\equiv H=H_0\left(\frac{r_0}{r}\right)^n$$

where

r_0=radius of the last stable orbit
$H_0=H_z$ at $r=r_0$

The magnetic field at $r>r_0$ in $\theta_p(H_p)$ and $\theta_q(H_q)$ is modified according to

$$S=\text{const.}=-\theta_p\frac{r}{H}\frac{\partial(H-H_p)}{\partial r}>0$$

$$T=\text{const.}=\theta_q\frac{r}{H}\frac{\partial(H_q-H)}{\partial r}>0$$

θ_p and θ_q are both smaller than 10°.

In m revolutions after r_0 the orbit between θ_p and θ_q is described by

$$P_m\equiv r_m-r_0=ke^{m\Lambda}\sin(\sqrt{1-n}\theta+\psi)$$

where

$$\cosh\Lambda=\cos 2\pi\sqrt{1-n}-\frac{T-S}{2\sqrt{1-n}}\sin 2\pi\sqrt{1-n}-\frac{TS}{2(1-n)}\sin(2\pi-\phi)\sqrt{1-n}\sin\phi\sqrt{1-n}>1 \quad (1)$$

$$\cot\psi=\frac{e^{\lambda}-\cos 2\pi\sqrt{1-n}+\frac{T}{\sqrt{1-n}}\sin(2\pi-\phi\sqrt{1-n}\cos\phi\sqrt{1-n}}{\sin 2\pi\sqrt{1-n}-\frac{T}{\sqrt{1-n}}\sin(2\pi-\phi\sqrt{1-n}\sin\phi\sqrt{1-n}}$$

and k depends on the amplitude of the free oscillation at $r<r_0$.

The vertical oscillation is damped provided

$$\cos\lambda=\cos 2\pi\sqrt{n}+\frac{T-S}{2\sqrt{n}}\sin 2\pi\sqrt{n}-\frac{TS}{2n}\sin(2\pi-\phi)\sqrt{n}\sin\phi\sqrt{n}<1 \quad (2)$$

T, S, and ϕ should be chosen to satisfy (1) and (2) and give a maximum Λ. Physical convenience should also be kept in mind when choosing ϕ.

One example of a peeler arrangement for producing a flux density distribution following the curves II of Fig. 4 is shown in cross-section in Fig. 8. Since the magnetic reluctance of the iron is high relative to that of the air, the lines of magnetic flux will gradually build up in the vicinity of the shim **5**, which is positioned outside of the peeler sector b so that it draws magnetic flux lines away therefrom, producing a decreasing field intensity in that sector. The peeler shims **7** and **7'** are used to build up the field intensity in the area adjacent the inner portion of the peeler sector b to compensate for the weakening of the field within r_0 by the shim **5**.

Fig. 9 shows the exemplary embodiment of the regenerative field apparatus. The shims **6** and **6'** are located within the regenerator sector c and therefore build up the field in that sector. The shims **8** and **8'** compensate for the strengthening of the field within r_0 by the shims **6** and **6'**.

The specific design of the peeler and regenerator apparatus which produces the desired modification of the conventional orbit controlling magnetic field is the preferred design but alternative means or methods for obtaining a desired field configuration known in the art may be used if desired.

In order not to interfere with the effect of the iron peeler and regenerator elements, the iron cylindrical tube **9** is

preferably placed azimuthally about half-way between the peeler and regenerator sectors.

Although a two-**D** type synchrocyclotron has been used to describe the invention, it should be understood that the invention is also applicable to the single-**D** type synchrocyclotron. The single-**D** type, as is well known in the art, uses a so-called "dummy **D**" to replace one of the **D**'s shown in the drawings.

Many modifications may be made of the preferred embodiment of the invention herein described without deviating from the broader aspects of the invention.

We claim:

1. A particle accelerator of the synchrocyclotron type having an orbit-controlling fixed magnetic field distribution described by the formula

$$n=\frac{-r}{B}\frac{dB}{dr}$$

where B is the magnetic field intensity at radius r from the axis of the field and n is a parameter whose average value is less than 0.75 in the vicinity of particle extraction, said accelerator having a vacuum chamber containing a pair of **D**'s, an extraction channel extending tangentially from and having its mouth adjacent the periphery of one of said **D**'s, field-weakening magnetic shim means disposed adjacent said one **D** and azimuthally in advance of said mouth, field-strengthening magnetic shim means disposed adjacent said one **D** and azimuthally beyond said mouth, and a pair of field-correcting magnetic shims disposed radially inward of each of the respective magnetic means to compensate for the effects of the respective magnetic means on the field radially inward of and adjacent said vicinity, one shim of each pair being disposed above said one **D**, the other shim of each pair being disposed below said one **D**.

2. A particle accelerator comprising an electromagnet of constant field including mutually spaced circular coaxial poles, a vacuum chamber between said poles with its median plane normal to the field axis, an extractor channel whose mouth is in the vicinity of particle extraction, said field being described by the formula

$$n=\frac{-r}{B}\frac{dB}{dr}$$

where n is a parameter whose average value is less than 0.75 in said vicinity, B is the magnetic field intensity, and r is the radial distance from the field axis, and particle extraction means comprising field-weakening magnetic means in said vicinity and in an azimuthal sector in advance of said mouth so that a particle entering said sector is sharply deflected radially outward toward said mouth and beyond that orbit in which the particle was moving immediately preceding such deflection, field-strengthening magnetic means in said vicinity and in an azimuthal sector azimuthally beyond said mouth so that a particle deflected outward as aforesaid but insufficiently to enter said mouth is sharply deflected radially inward beyond that orbit in which said particle was moving immediately preceding such inward deflection, whereby said particle moves under the influence of both of said magnetic means in an orbit having a radial oscillation whose amplitude progressively increases with succeeding revolutions of said particle until said particle enters said mouth, field-strengthening magnetic means disposed radially inward of the first magnetic means and arranged to compensate for the field-weakening effect of said first magnetic means radially inward beyond said vicinity, and field-weakening magnetic means disposed radially inward of the second magnetic means and arranged to compensate for the field-strengthening effect of said second magnetic means radially inward beyond said vicinity.

3. The structure of claim 2, characterized in that said magnetic means collectively comprise iron shims disposed within said chamber and symmetrically with respect to said plane.

4. A particle accelerator comprising an electromagnet of constant field including mutually spaced coaxial poles, a vacuum chamber between said poles with its median plane normal to said field axis, an extractor channel whose mouth is in the vicinity of particle extraction, said field being described by the formula

$$n=\frac{-r}{B}\frac{dB}{dr}$$

where n is a parameter whose average value is less than 0.75 in said vicinity, B is the magnetic field intensity, and r is the radial distance from the field axis, and particle extraction means comprising field-weakening magnetic means in said vicinity in an azimuthal sector in advance of said mouth so that a particle entering said sector is sharply deflected away from said axis and toward said mouth, field-strengthening magnetic means in said vicinity in an azimuthal sector azimuthally beyond said mouth so that a particle deflected outward as aforesaid but insufficiently to enter said mouth is sharply deflected toward said axis, whereby said particle moves in an orbit having a radial oscillation whose amplitude progressively increases with suceeding revolutions of said particle until said particle enters said mouth, and magnetic means disposed in said sectors and formed to compensate for the field-modifying effects of the first two magnetic means on the portions of said field located radially inward of said vicinity.

5. The structure of claim 4, characterized in that all of said magnetic means are arranged in said chamber and symmetrically to said plane.

6. The structure of claim 4, characterized in that all of said magnetic means are arranged in said chamber and symmetrically to said plane, said third magnetic means comprising pairs of shims disposed out of said plane.

7. A particle accelerator including means for accelerating particles in a spiral orbit, orbit-controlling means comprising an electromagnet having a pair of mutually spaced poles at constant potential providing a constant magnetic field described by the formula

$$n=\frac{-r}{B}\frac{dB}{dr}$$

where n is a parameter whose average value in the vicinity of particle extraction is less than 0.75, B is the intensity of the magnetic field, and r is the radial distance from the axis of said field, a vacuum chamber in which the particles are accelerated, said chamber being disposed in said field with the median plane of said chamber normal to said field, a particle extraction channel extending from the periphery of said chamber and having its mouth adjacent said periphery, and means located in said chamber for radially oscillating the particle orbit in the vicinity of particle extraction with increasing amplitude on successive revolutions to enable the particle to escape into said channel without striking the lip of said channel, said oscillating means comprising field-weakening magnetic shim means adjacent said periphery and in advance of said mouth and in said field and arranged to maintain said field in a constant weakened condition in a small azimuthal sector whose inner limit is at the radius of the last equilibrium orbit of the particle, said oscillating means further comprising field-strengthening magnetic shim means adjacent said periphery and following said mouth and in said field and arranged to maintain said field in a constant strengthened condition in a small azimuthal sector whose inner limit is at the radius of the last equilibrium orbit of the particle.

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