June 28, 1960 | H. F. KAISER | 2,943,265

ELECTRON CYCLOTRON

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FIG. 1

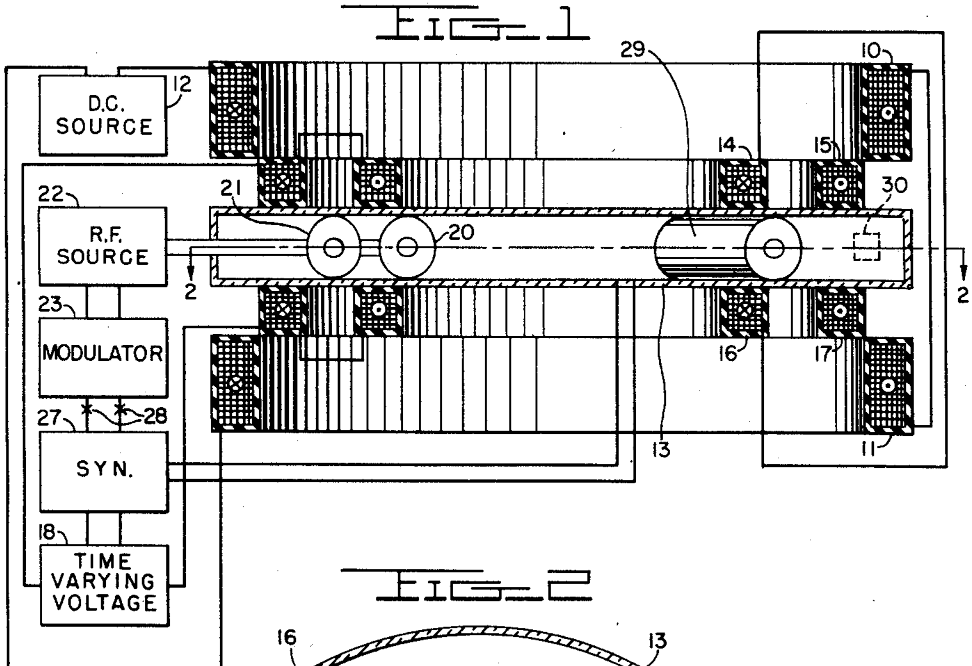
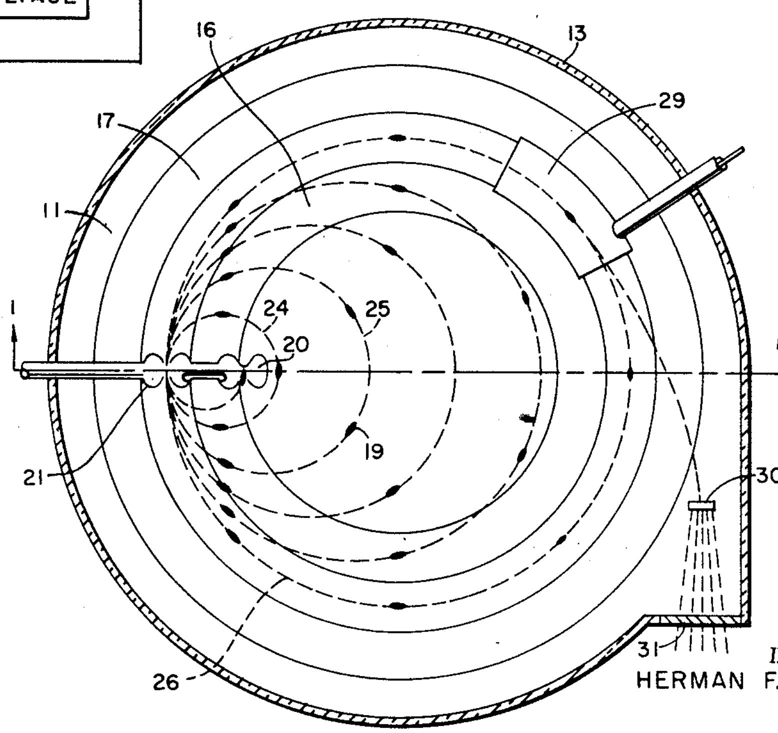


FIG. 2



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ELECTRON CYCLOTRON

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FIG. 5

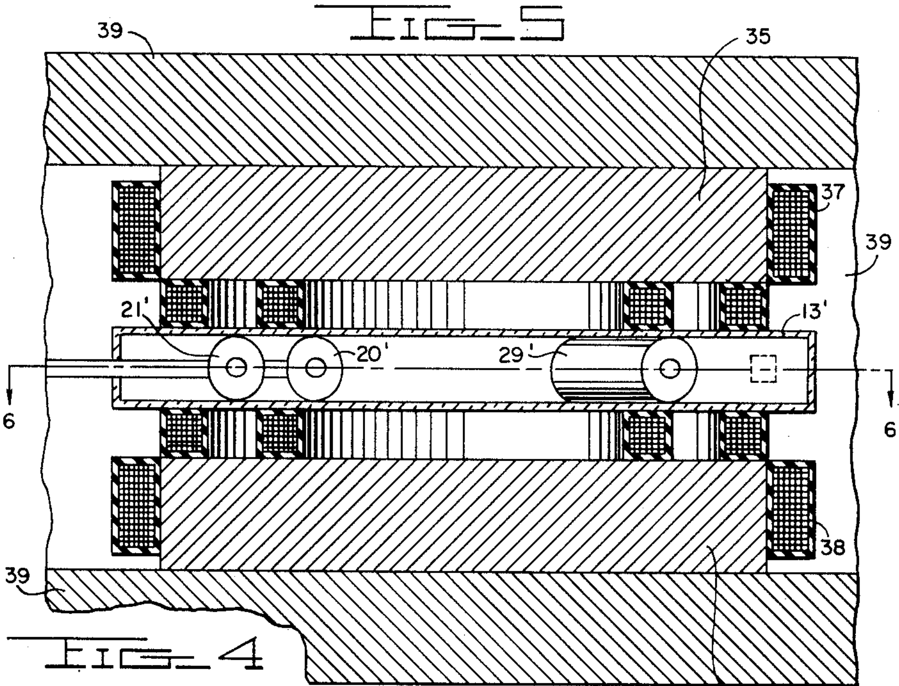


FIG. 4

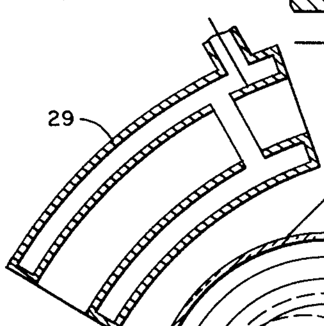


FIG. 6

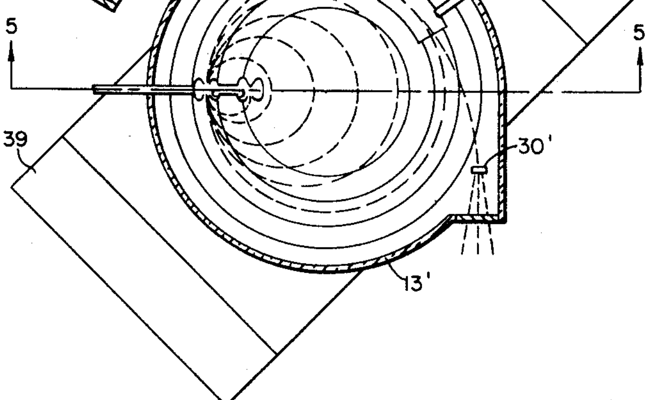
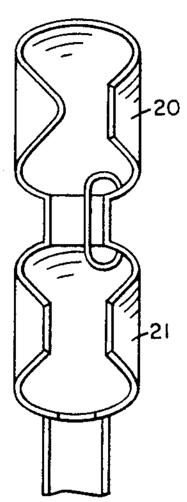


FIG. 3



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ELECTRON CYCLOTRON

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FIG. 7

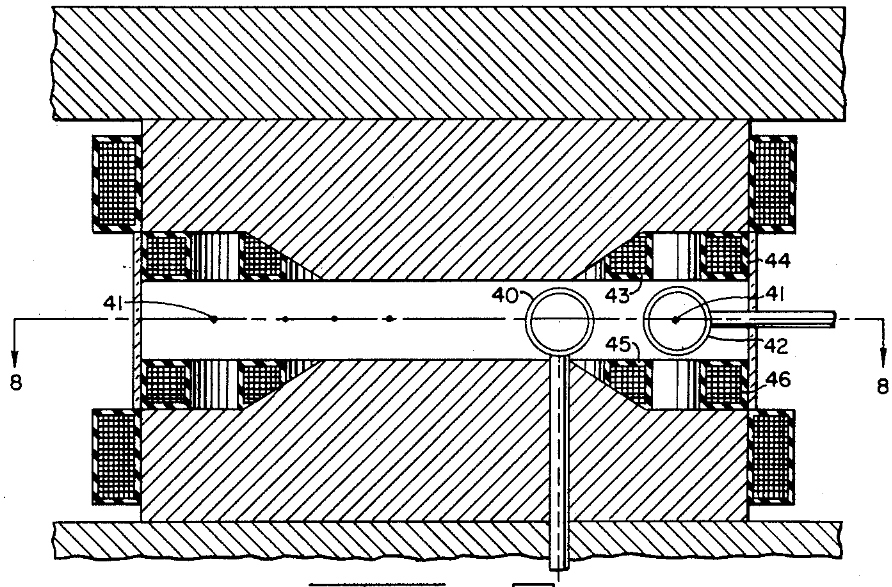

FIG. 8

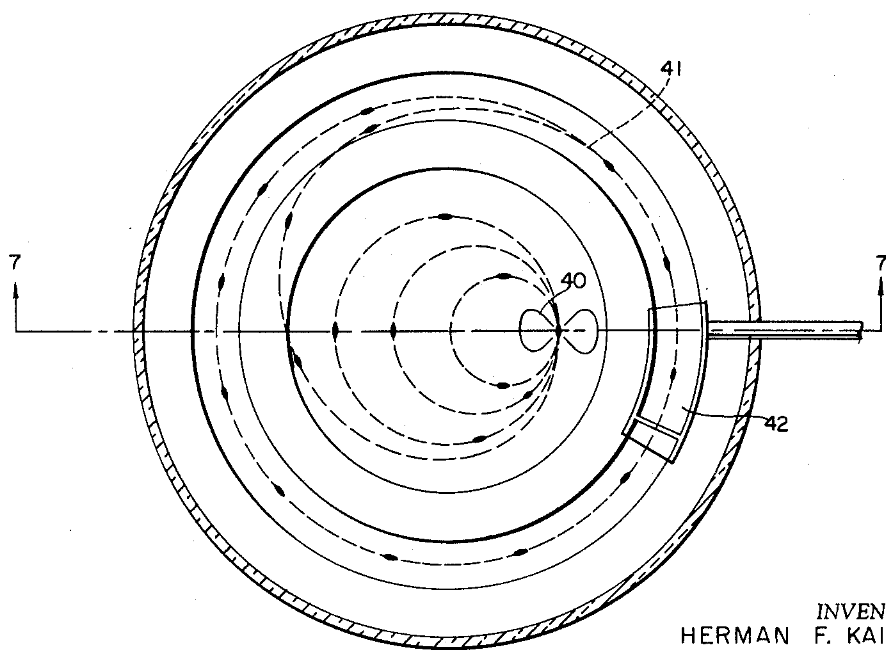

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FIG. 9

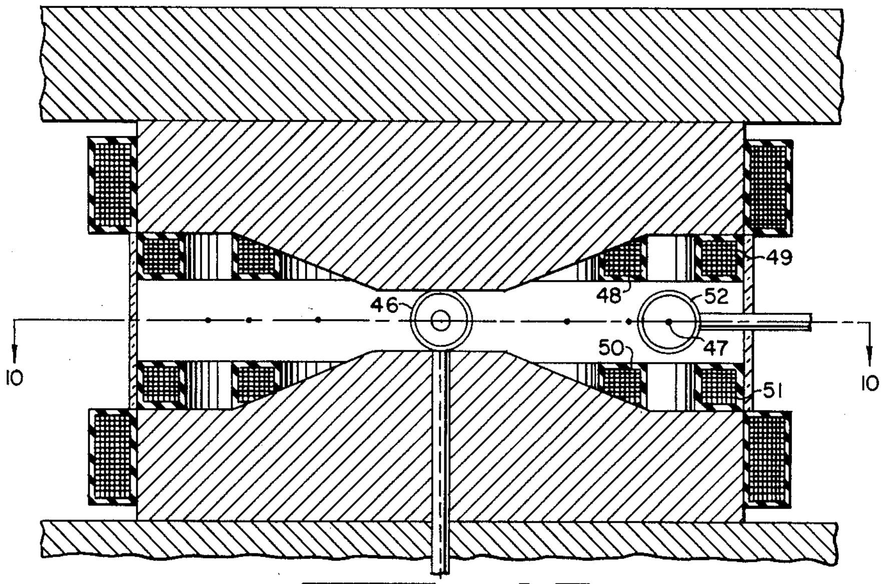

FIG. 10

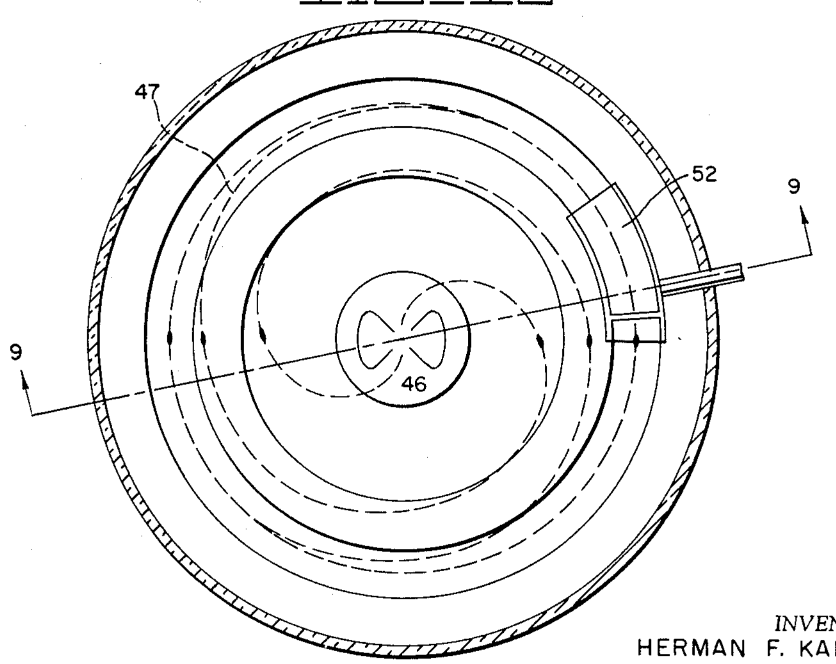

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FIG. 11

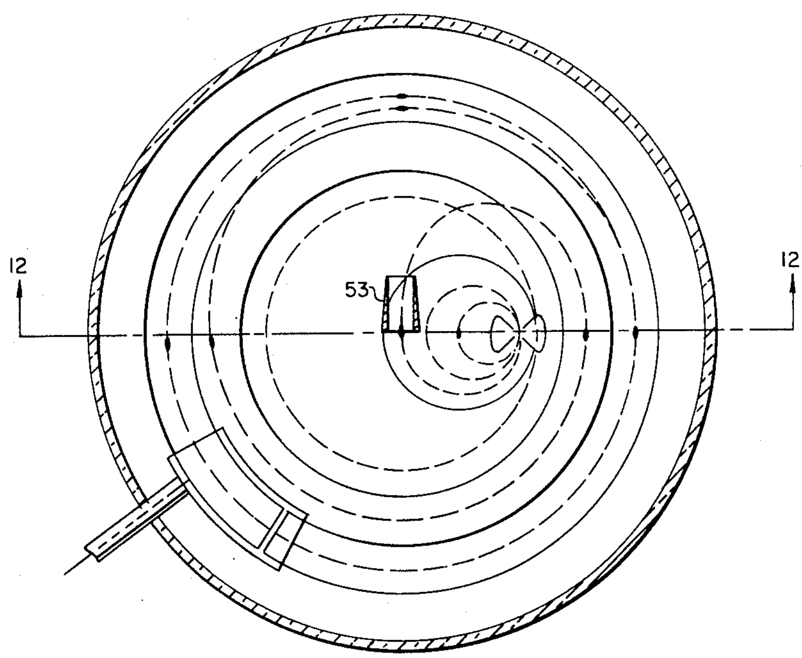
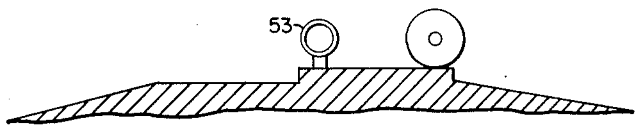


FIG. 12



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United States Patent Office

2,943,265

Patented June 28, 1960

2,943,265

ELECTRON CYCLOTRON

Herman F. Kaiser, Washington, D.C., assignor to the United States of America as represented by the Secretary of the Navy

Filed Feb. 8, 1957, Ser. No. 639,126

9 Claims. (Cl. 328—234)

(Granted under Title 35, U.S. Code (1952), sec. 266)

The invention described herein may be manufactured and used by or for the Government of the United States of America for governmental purposes without the payment of any royalties thereon or therefor.

The present invention relates in general to high-energy, charged particle accelerators and has particular reference to a high energy electron accelerator of the circular orbit type using the principle of the electron cyclotron. According to this principle, electrons are accelerated through successive orbits of increasing radius to relativistic velocities by the combined action of a static magnetic guide field and a time varying accelerating electric field such as produced by a resonant cavity accelerator, accelerating the electrons step-by-step by repeated transit of the electrons through the electric accelerating gap where the orbits are cotangential.

An object of the invention is the provision of an electron accelerator of reduced bulk and weight relative to the energy attainable, affording that compactness and convenience essential in research apparatus and special practical purposes where compactness and portability are essential.

Another object is the provision of an accelerator of the electron cyclotron type in which electrons in motion may gain additional energy after acceleration to relativistic velocities near the speed of light.

A further object is the provision of a microtron or electron accelerator of the electron cyclotron type in which a charge of electrons may be trapped in an orbit of maximum attainable velocity and then further accelerated to an energy depending only on the orbital radius and the magnetic field strength attainable in a rising magnetic guide field.

A further object is the provision of a small, compact, easily used electron accelerator capable of furnishing electrons in high density bunches yet at low duty cycles whereby average electron current is small and attendant radiation hazard minimized.

Various other objects and advantages of the invention will become apparent upon perusal of the following specification and the accompanying drawings in which:

Fig. 1 is a diagrammatic view in vertical, axial cross section on the line 1—1 of Fig. 2.

Fig. 2 is a diagrammatic view in horizontal section on the line 2—2 of Fig. 1.

Fig. 3 is an enlarged cross section view of the resonators shown diagrammatically at 20—21 in Fig. 2.

Fig. 4 is an enlarged section through the electron accelerator shown diagrammatically at 29 in Fig. 2.

Fig. 5 is a diagrammatic view of a modification using iron core magnets.

Fig. 6 is a diagrammatic view of horizontal section through the mid-plane of the device on line 6—6 of Fig. 5 and on a reduced scale.

Fig. 7 is a diagrammatic view in vertical axial section on line 7—7 of Fig. 8 of a further modification.

Fig. 8 is a diagrammatic horizontal section on the line 8—8 of Fig. 7.

Fig. 9 is a diagrammatic view in vertical axial section on the line 9—9 of Fig. 10 of another modification.

Fig. 10 is a diagrammatic horizontal section on line 10—10 of Fig. 9.

Fig. 11 is a diagrammatic horizontal section through the median plane of a further modification.

Fig. 12 is a diagram in section on line 12—12 of Fig. 11.

Referring to the drawings in detail and first to Figs. 1 and 2, the apparatus provides a pair of magnetic field coils **10** and **11** without iron cores, spaced axially one above the other to form a pair of Helmholtz coils for generation of a substantially uniform, static magnetic field within them, these coils being energized by current from a suitable source of direct current **12** passing in the same directions through both coils. A flat circular chamber **13** of dielectric material is positioned between and coaxially with the coils **10** and **11** so as to be traversed perpendicular to its median plane by the flux generated by the coils **10—11**.

A second double set of Helmholtz coils **14—15**, **16—17** (in which currents flow oppositely as shown in each set) are positioned in the gap between the coils **10—11**, above and below the vacuum chamber **13**, near the outer margin of the chamber to there provide a local auxiliary guide field along an outer circular zone within the chamber, so as to lie in the region of a chosen outer particle orbit set up in a manner to be presently described. This second set of coils is energized to produce a time modulated field as by a suitable power source **18** with time modulated voltage, which may be of any known or other suitable type supplying a voltage pulse of the desired rate of rise, to produce a field in the space between sets of coils **14—15** and **16—17** rising at a rate for example in the neighborhood of 10^9 gauss per second.

Charged particles to be accelerated, in the present instance bunches of electrons **19**, Fig. 2, are injected into the chamber **13** and repeatedly accelerated into orbits of increasing radius in the manner of a microtron or electron-cyclotron, by a pair of high voltage cavity resonators **20—21** located in the vacuum chamber near one side. The resonators are excited at a radio frequency say in the S-band or X-band in the known manner of a microtron or electron-cyclotron, as by a conventional magnetron and tuner arrangement **22**, pulsed by a suitable modulator **23**. With a pulsed power of the order of 100 kw., electric fields of about a half million volts per centimeter may be attained at S-band frequency (9,375 mc./s.), amply sufficient for field emission. The injector resonator **20** thus operates by field emission to inject a bunch of electrons into the chamber **13** normal to the magnetic field, for each resonator period, which bunches of electrons take circular paths through the gap field of the driving resonator **21** in proper phase for further acceleration into successive orbits of increasing radius.

There is thus built up in the vacuum chamber for each pulse of radio frequency energy fed to the resonators, a plurality of bunches of electrons **19** traveling in orbits **24**, **25**, etc. of increasing radius. The periods of successive electron orbits usually differ by one radio frequency period of the resonators **20**, **21** so that one new bunch of electrons is added as the number of an orbit increases. Thus an orbit pattern is formed as indicated in Fig. 2. In any given orbit the energy of the electrons is determined simply by the number of the orbit.

A particular orbit **26** of the microtron orbit pattern is designed to be situated in the magnetic field region of coils **14—17**, its center and radius being the same as the center and radius of the vertical symmetry axis of the cross section of the coil system **14—17**. This orbit with a definite number of electron bunches comprising an orbital charge of definite amount will exist at any time during operation of the driving resonator **21**. If now at an arbitrary instant of time, coil system **14—17** is energized in such a way that the field strength increases in the system in proportion to the energy gain of a particle in this orbit this particle will in principle continue to follow the path of orbit **26** at substantially constant radius.

It will be seen that the energy gains per turn in the microtron orbits are large (appreciable fractions of an electron rest mass energy). This will require magnetic field rates of rise that are very large, but not impossible of attainment in an air core coil system of the type shown in Fig. 1. The major difficulty to be encountered, with this way of operating the apparatus is the spiraling of the electrons due to change in magnetic field during the time required to pass around orbit **26**. This requires special modification in the design of the super magnetic field system **14—17**, to correct for the orbit spiraling and permit motion at substantially constant radius.

To avoid the two difficulties mentioned in the above paragraph, it is better (1) to operate the driving resonator **21** at a modest amplitude (a low energy-gain microtron mode), (2) to use a larger microtron field region of lower field strength (as required by the lower mode), permitting thus a larger number of electron bunches or total orbit charge. The rate of field rise required in magnet system **14—17** to maintain substantially constant radius will be smaller and the spiraling or departure from initial radius over an orbit turn reduced to an amount tolerable by the radial stability possible in the field system and by the aperture of the driving resonator. Under such conditions the operation of the apparatus will be simplified to the energizing of the coil system (**14—17**) at any arbitrary time point after the microtron orbit **26** has been set up (a time considerably less than .1 microsecond). In this form of operation the particles are accelerated in the manner of the conventional synchrotron in which any departure of the orbital energy from the energy corresponding to the average magnetic field prevailing during an orbital period is corrected by changes of phase in particle passage through the resonator, this imparting additional energy when the particle energy is below the required average subtracting when above.

When desired, the modulator **23** may be synchronized relative to the cycle of the time-varied super field in known manner as by a modulator synchronizing circuit **27** arranged to be operatively connected with the modulator through a switch **28** or equivalent, the synchronizing circuit being controlled in known manner from the time varying voltage source to cause the radio frequency source **22** to pulse the resonators for a period, starting a sufficient time before the start of the field rise from zero, to build up a multiple orbit pattern reaching to the super field zone, and to continue through a desired portion of the rise time of the super field.

As an alternative way of operating the accelerator, one may at an arbitrary instant after microtron orbit **26** is set up, de-energize resonator **21** in a few cycles to zero amplitude. This may be accomplished by methods known to the art such as interval short circuit loading of the resonator by an auxiliary discharge, or application of a precise radio frequency pulse with voltage 180° out of phase with the resonator voltage, analogous to the stopping of a mechanical oscillator by an externally produced driving force of the same period but 180° out of phase with the oscillator.

With resonator **21** de-energized in this way only some of the electron bunches existing in orbit **26** at this time-point will receive energy from the resonator and therefore fail to continue on orbit **26**. Those receiving no energy continue on this orbit until dissipated by gas scattering. If now the coil system **14—17** is energized to bring the super magnetic field on orbit **26** up slowly with time and at the same time resonator **21** is re-energized to oscillate at a low amplitude the particles in each electron bunch will be accelerated to progressively higher energies with time as in conventional synchrotron operation. As an alternative procedure at this point resonator **29** (a conventional coaxial resonator commonly used in synchrotrons) may be energized instead of resonator **21**. Since the frequency of resonator **29** is usually chosen as the orbital particle rotation frequency (in orbit **26**), the subsequent acceleration process will differ somewhat in that a "bunching of all the particle bunches" will precede the final synchrotron acceleration. The above mentioned operation of resonators **21** and **29** may be synchronized with the cycle of operation of the super guide field through the synchronizer **27**, using the voltage source **18** as a time base.

The accelerated electrons may be utilized in any known or other suitable manner as by ejection from the instrument for outside use accomplished by a variation in the outer magnetic field or by the energization of an electric deflecting field, timed in proper relation to the period of rise of the time modulated field, to effect diversion of electrons at a time near the time of their maximum energy acceleration, into a properly shielded exit path. As a specific example the accelerated electrons may be utilized for the production of high energy radiation by the use of a target **30** placed slightly outwardly of the outermost orbit whereby outward diversion of the accelerated particles from that orbit due to reduction in rate of rise in field strength of the super field near the end of its period of rise, will cause the accelerated particles to strike the target for conversion into high energy radiation to be radiated out through a suitable window **31** transparent to such radiation.

When the rate of field rise in the field coil system **14—17** of Fig. 1 is not so high that such rate of rise cannot be attained in proximity to iron members, the modification of Figs. 5 and 6, may be used. This permits the use of an iron yoke **39** and pole pieces **35—36** with D.C. coils **37, 38** for production of the stationary microtron magnetic field.

A further modification (most conveniently but not necessarily attained by use of an iron membered magnet system) is shown in Figs. 7 and 8. This differs from arrangements described above only in that the final microtron orbit is artificially guided into a circular orbit which does not rethread the driving microtron resonator **40**. As shown in Figs. 7 and 8 the resonator **40** is located in a flat (uniform, stationary) magnetic field near the center of the magnet system. The flat region is limited so that only a few complete microtron orbits may be set up. After this the next microtron orbit will move into a field decreasing with radius according to an inverse power law. It is known from the theory of a device known as the spiral orbit spectrometer that the motion in this orbit will be a spiral with spiral radius increasing but not indefinitely so that after some turns the spiral turns tend to converge into a circular orbit **41** of final radius determined by the particle momentum alone. (This property is involved in the device mentioned above to sort particles of different momentum.) With the field system suitably designed to give a converging orbit circle corresponding to the nearly homogeneous momentum of the final microtron turn, a synchrotron resonator **42** similar to resonator **29** of Fig. 1 is suitably located so that particles in this circular orbit will be accelerated by the combined action of the resonator and a rising field locallized upon the orbit by a coil system **43—46** similar to coils **14—17** of Fig. 1. An advantage of this modification is that the resonator **42** may be started at any arbitrary time-instant after orbit **41** is set up and the coil system **43—46** thereafter energized to a small interval of time after the start of resonator **42** to properly bunch the electrons distributed in orbit **41**.

A further modification shown in Figs. 9 and 10 consists in placing the cavity injector resonator **46** at the center of the magnet system and adjusting the magnetic field distribution so that the first microtron orbit is not completed but proceeds directly as described for Figs. 7 and 8 into a spiral orbit which finally converges into a circular orbit **47**. Upon this orbit are located coils **48—51** for producing a field localized upon this orbit and which may be caused to increase in time as required for simultaneous conjunctive operation with accelerating resonator **52** similar to operation of coils **14—17** with resonator **29** of Fig. 1. An advantage of this modification is that the field emission electron output from the cavity resonator **46** will be utilized for both half cycles of the cavity voltage vs. time curve. A further advantage is that the electrons are ejected radially from the magnet center as envisaged in the theory of the spiral orbit spectrometer. This is only approximately realized in the arrangement of Fig. 8 but it may be noted the correction of central radial departure may be produced with the arrangement of Fig. 11 by letting the final microtron orbit pass over the center of the magnet system and into a short magnetic shielding tube **53**, which serves the purpose of straightening the trajectory into a straight line, and into the region where the magnetic field decreases with radius in the manner required by the spiral orbit spectrometer theory.

Obviously many modifications and variations of the present invention are possible in the light of the above teachings. It is therefore to be understood that within the scope of the appended claims the invention may be practiced otherwise than as specifically described.

What is claimed is:

1. A charged particle accelerator comprising a static magnetic guide field, means for injecting a bunch of charged particles into the guide field to be guided through a first circular orbit, electrostatic accelerating means applied to said orbit for successively accelerating said bunches of charged particles into cotangential circular orbits of increasing radius and higher velocity, and means producing a magnetic field varying with time superimposed upon said static field at the outermost orbits.

2. A charged particle accelerator comprising a flat circular evacuated chamber element enclosing space for a plurality of circular orbits having substantially parallel orbital planes, means for maintaining a static magnetic guide field directed through said chamber axially thereof, means for injecting bunches of charged particles into the guide field within and near one side of the chamber to be guided through a first circular orbit near one side of the chamber, electrostatic accelerating means situated in the path of said first orbit for successively accelerating said bunches of charged particles into cotangential circular orbits of increasing radius and higher velocity, and means for producing a localized magnetic guide field increasing with time, superimposed upon the static guide field in aiding relation and restricted to an annular zone including an outer orbit, whereby a charged particle of increasing energy will be trapped in the said outer orbit during the increase in said localized magnetic field.

3. A charged particle accelerator comprising, an evacuated chamber, means for producing a static magnetic guide field in said chamber, a source of electrons contained in said chamber, a resonant cavity electrostatic accelerator in the chamber accelerating electrons from said source into orbits of increasing radius and cotangential where they pass through the cavity accelerator, means for producing a magnetic guide field varying with time superimposed upon said static magnetic field and restricted substantially to an annular zone including only the larger orbits entered by electrons of substantially the highest velocity attainable in the static magnetic field whereby additional passages of electrons through said annular zone and the cavity accelerator will impart further energy to said electrons.

4. A charged particle accelerator comprising a circular evacuated chamber, means for producing a steady magnetic guide field traversing the chamber parallel to the axis of the chamber, means for superimposing upon said steady field a varying magnetic guide field of the same polarity and confined to an outer circular zone within the chamber, and means within the chamber for setting up a pattern of electron cyclotron cotangential circular orbits of increasing radius reaching into said outer circular zone.

5. An electron accelerator comprising an injector cavity resonator and an accelerator cavity resonator, an evacuated chamber constructed to enclose a circular zone including said resonators, means for producing a static magnetic guide field parallel to the axis of the circular zone, said injector resonator being positioned to inject electrons through the guide field in an orbit passing through the accelerator resonator, said accelerator resonator being positioned to repeatedly accelerate said electrons into orbits of increasing radius cotangential at the point where they pass through the accelerator, means for producing a magnetic guide field varying with time and superimposed upon said static magnetic field in an annular zone containing the orbits of substantially maximum radius whereby further energy may be imparted to said latter electrons at each passage through the said resonator accelerator while held in said outer zone by the time modulated guide field.

6. An electron accelerator comprising a vacuum chamber, means for maintaining a static magnetic field inside the chamber coaxial with a given circular space in said chamber, a source of radio frequency energy, an injector cavity resonator energized by said source and situated in the circular space near one side thereof for injecting bunches of electrons into a circular orbital path, a driving cavity resonator energized by said source and having an iris gap situated in said orbital path for repeatedly accelerating said bunches of electrons into successive orbital paths of increasing radius cotangential where they pass through the iris gap, means for generating a magnetic field increasing with time superimposed upon the static magnetic field in aiding relation thereto, and restricted in cross sectional area to an annular zone containing a given outer electron orbit, a second driving cavity resonator energized by said source of radio frequency energy situated to include said outer orbit, and means for energizing said injector resonator for a given period of time prior to a portion of the increasing period of said superimposed magnetic field.

7. A charged particle accelerator comprising a flat circular evacuated chamber element enclosing space for a plurality of circular orbits having substantially parallel orbital planes, means for maintaining a static magnetic guide field directed through said chamber transversely of said orbits substantially uniform over a central portion of said orbital space and decreasing with radius from the outer limit of said central portion according to an inverse power law, a microtron cavity resonator situated within and to one side of the said central portion of the orbital space for injecting bunches of electrons by field emission into the guide field to be repeatedly circulated through the resonator into cotangential circular orbits of increasing radius and higher velocity, means for producing a localized magnetic guide field increasing with time, superimposed upon the static guide field in aiding relation and restricted to an annular zone including an outer orbit beyond the said central portion, and a synchrotron driving resonator positioned to be threaded by said outer orbit, whereby a charged particle of increasing energy will be trapped in the said outer orbit during the increase in said localized magnetic field.

8. An electron accelerator comprising a flat circular evacuated chamber element enclosing space for a plurality of circular orbits having substantially parallel orbital planes, means for maintaining a static magnetic guide field directed through said chamber transversely of said orbits substantially uniform over a central portion of

said orbital space and decreasing with radius from the outer limit of said central portion according to an inverse power law, a microtron cavity resonator situated within the said central portion of the said orbital space for ejecting bunches of electrons by field emission through said central portion to said outer limit of the central portion, means for producing a localized magnetic guide field increasing with time, superimposed upon the static guide field in aiding relation and restricted to an annular zone including an outer orbit beyond the said central portion, and a synchrotron driving resonator positioned to be threaded by said outer orbit, whereby a charged particle of increasing energy will be trapped in the said outer orbit during the increase in said localized magnetic field.

9. An electron accelerator comprising a flat circular evacuated chamber element enclosing a space for a plurality of circular orbits having substantially parallel orbital planes, means for maintaining a static magnetic guide field directed through said chamber transversely of said orbits substantially uniform over a central portion of said orbital space and decreasing with radius from the outer limit of said central portion according to an inverse power law, a microtron cavity resonator situated within and to one side of the central portion of the orbital space for injecting bunches of electrons by field emission

into the guide field to be repeatedly circulated through the resonator into cotangential circular orbits of increasing radius and higher velocity, a magnetic shielding tube situated in the path of an outer orbit within the central portion for straightening the trajectory of electrons in that orbit into the region where the magnetic field decreases with radius, whereby the electrons spiral into an outermost orbit radially beyond said central portion, means for producing a localized magnetic guide field increasing with time, superimposed upon the static guide field in aiding relation and restricted to an annular zone including the said outermost orbit beyond the said central portion, and a synchrotron driving resonator positioned to be threaded by said outermost orbit, whereby an electron of increasing energy will be trapped in the said outermost orbit during the increase in said localized magnetic field

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