Jan. 19, 1960 LEE C. TENG 2,922,061

PARTICLE ACCELERATOR

Filed Jan. 31, 1957 2 Sheets-Sheet 1

Fig-1

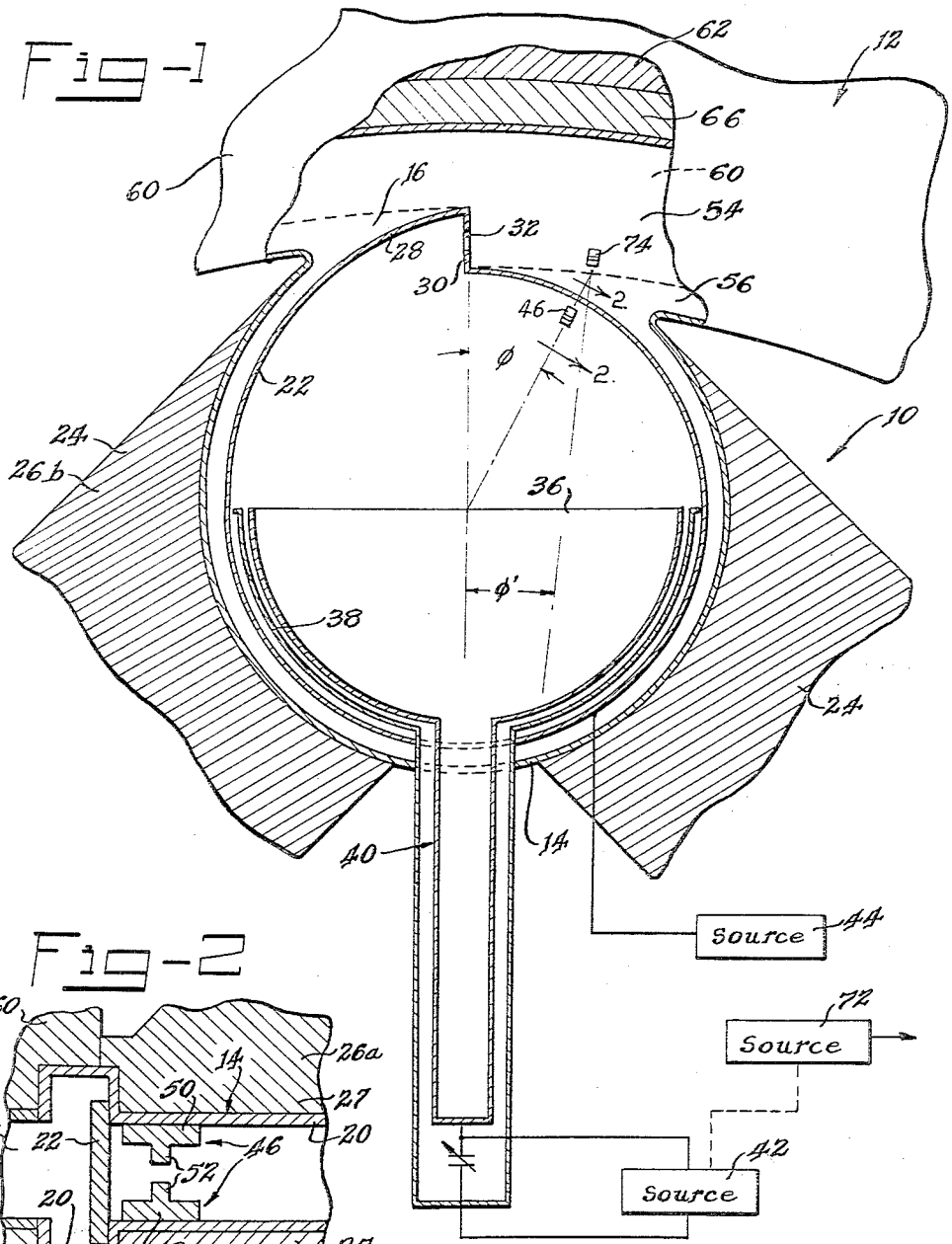


Fig-2

INVENTOR.
Lee C. Teng

BY
Roland A. Anderson
Attorney

Jan. 19, 1960 LEE C. TENG 2,922,061

PARTICLE ACCELERATOR

Filed Jan. 31, 1957 2 Sheets-Sheet 2

Fig-3

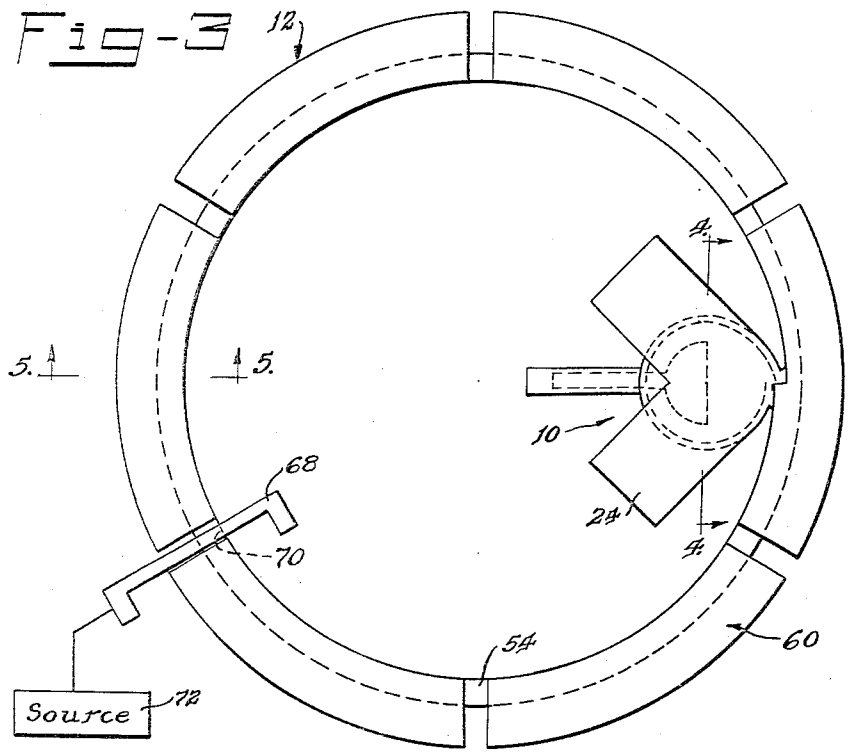


Fig-4

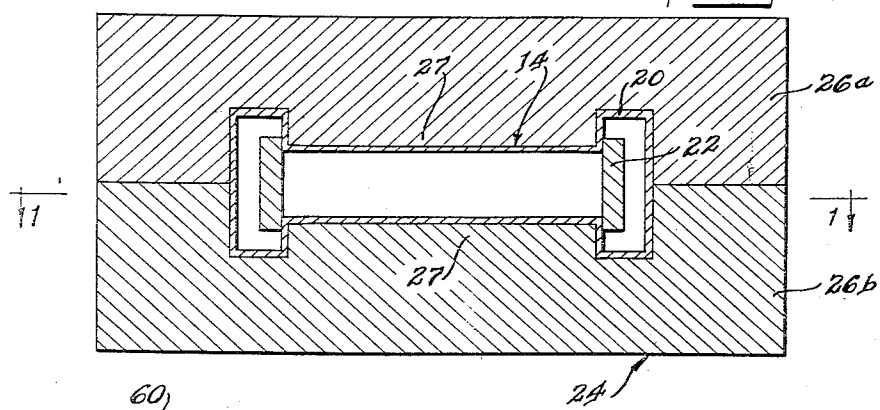
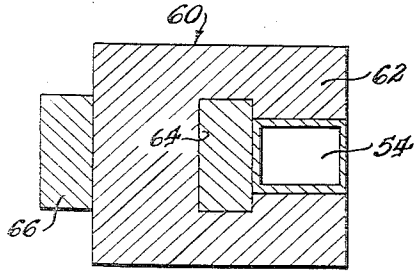


Fig-5



INVENTOR.
Lee C. Teng

BY
Roland A. Anderson
Attorney

United States Patent Office 2,922,061 Patented Jan. 19, 1960

2,922,061

PARTICLE ACCELERATOR

Lee C. Teng, Chicago, Ill., assignor to the United States of America as represented by the United States Atomic Energy Commission

Application January 31, 1957, Serial No. 637,595

7 Claims. (Cl. 313—62)

The present invention relates generally to particle accelerators, and more particularly to devices for transferring particles from one accelerator to another.

Circular accelerators have proved to be a useful tool in producing high energy particles. In such machines, charged particles, such as protons and deuterons, are introduced into an orbit and revolve about the axis of the accelerator gaining energy with each revolution. The radius of the orbit of the charged particle is a function of the energy of the particle and the magnetic field traversing the orbit. As a result, the orbit radius of the particle increases with increased energy, the magnetic field being held constant, or the radius of the orbit may be held constant by increasing the magnetic field as the energy of the charged particle increases. In most ring accelerators of fixed magnetic field designed for high energy, the magnetic field increases from a minimum adjacent to the axis of the machine to a maximum at the periphery thereof, so that the radius of the orbit of the charged particles increases only slightly with increased energy. In the case of cyclotrons, the charged particles are introduced at substantially zero energy approximately on the axis of the machine, and the cyclotron accelerates these particles causing them to move out toward the periphery of the machine to a maximum energy. In most ring accelerators, the particles are introduced into an orbit located on the inner boundary of the machine at a substantial energy, and the increased energy of the particles due to acceleration causes the particles to move only slightly toward the outer periphery of the machine due to the greatly increased magnetic flux in this region.

Acceleration of the particles within the accelerator is achieved by synchronizing an alternating electrical field with the position of a group of particles in the accelerator. At low energies, the electrical field may operate at a constant frequency, however, as the particles are accelerated to higher energies, the frequency of the accelerating potentials changes.

The maximum energy obtainable with any given circular accelerator is limited by the maximum magnetic field which is attainable. As a practical matter, the maximum magnetic field attainable is limited by the saturation density of the magnet. Since iron is universally employed in the magnets of accelerators at the present time, it is considered that the maximum magnetic field attainable is approximately 20 kilogauss. As a result, very high energy particles can only be achieved with a large radius for the final accelerating orbit. On the other hand, it has not been possible to inject particles of high energy into the inner orbits of an accelerator, thus requiring a single accelerator to cover a wide energy range. Heretofore, particles could be injected into an accelerator at energies of only approximately 50 mev., or less. This fact effectively limits the diameter of a ring accelerator. Further, the minimum magnetic field which may be employed in an accelerator is of the order of 50 gauss, because of the effects of terrestrial and stray magnetism. As a result, the low energy particles must be injected into a substantial magnetic field, thus resulting in a relatively small diameter orbit.

It is one of the objects of the present invention to provide a device for injecting charged particles into an accelerator which may be employed regardless of the energy of the particles. In this manner, particles of high energy may be injected into an accelerator, such as a ring accelerator, and further accelerated to a much higher energy than has heretofore been possible. The high energy accelerator may be a ring accelerator of much larger diameter than any that has heretofore been possible. Since the accelerator need not handle the range of energies previously required, substantial amounts of iron or other magnetic metal may be eliminated from the magnet of the accelerator.

It is a further object of the present invention to provide a device for accelerating charged particles which includes at least two cascaded accelerators. As a result, the energy of the particles injected into the low energy orbit of the higher energy accelerator will be very much greater than the energy of the particles previously injected into an accelerator, resulting in simplification of the design of the higher energy accelerator. The particles may be raised in the initial accelerator to any desired energy, depending principally upon the complications in the design of the initial accelerator which are to be undertaken.

The design of the high energy accelerator is greatly simplified when the energy of the particles injected into the accelerator is high. Since the energy range handled by the higher energy accelerator is reduced by this fact, it is not necessary to frequency modulate the accelerating potentials over as wide a frequency range as is required with accelerators in which low energy particles are injected. It is much easier and economical to build a high potential radio frequency generator which is frequency modulated over a narrow range than it is to construct such a generator which is frequency modulated over a wide range. In addition, substantial quantities of magnet material are no longer required, since it is unnecessary to accelerate the particles over the range of radii required when the energy of injection of the particles is low. Further, the emerging high energy beam from the accelerator may be obtained at greater intensity than has been previously possible at high energies.

These and additional advantages of the present invention will become readily apparent to those skilled in the art from a further reading of this disclosure, particularly when viewed in the light of the drawings, in which:

Figure 1 is a sectional view of a particle accelerator employing a synchrocyclotron and fixed field alternating gradient ring accelerator disposed in cascade according to the teachings of the present invention;

Figure 2 is a sectional view taken along the line 2—2 of Figure 1;

Figure 3 is a top elevational view of the particle accelerator illustrated in Figure 1, partly schematic;

Figure 4 is a sectional view taken along the line 4—4 of Figure 3; and

Figure 5 is a sectional view taken along the view 5—5 of Figure 3.

Charged particles may be accelerated according to the teachings of the present invention by cascading accelerators. The outer orbit of the first accelerator is introduced into the low energy orbit of the second accelerator by a transfer device. The transfer device includes a deflector in the first accelerator to displace the outer high energy orbit outwardly from its normal path to pass through a slit in the first accelerator and into the second accelerator. Within the second accelerator, an inflector is positioned to change the orbit of these particles (now the

low energy particles) in the high energy accelerator to cause them to rotate about the axis of the accelerator.

The applicant's device for transferring particles from one accelerator to another may be employed with any type of circular accelerator and is not limited in the energy of the particles being transferred. It is, of course, most likely that the second accelerator will be a ring-type accelerator, since substantial energy is being injected into the accelerator and there is no reason to provide the very low energy orbits which are characteristic of cyclotrons. It is also likely that the low energy accelerator will be of the cyclotron-type, since a cyclotron is capable of accelerating particles from essentially zero energy on up to the maximum energy obtainable in the particular machine. However, the present invention may also be practiced by cascading cyclotrons, or ring accelerators. For illustrative purposes, the figures illustrate the low energy accelerator as a synchrocyclotron **10**, and the high energy accelerator as a fixed field alternating gradient ring-type accelerator **12**.

The synchrocyclotron **10** has an air impermeable housing **14** of generally cylindrical shape. One portion **16** of the housing **14** protrudes outwardly from the cylindrical remainder thereof. The peripheral portions of the housing, designated **20**, also protrude outwardly from the other portions of the housing in a rectangular manner to form a generally H-shaped housing cross section, as illustrated in Figure 4. The housing **14** is constructed of nonmagnetic material and is evacuated in a conventional manner. The protruding portion **20** of the housing **14** contains a generally annular coil **22** which is electrically insulated from the housing and forms the coil of an electromagnet. A core **24** of the electromagnet comprises a pair of bars **26***a* and **26***b* which are disposed on opposite sides of the housing **14** in contact with each other. The confronting surfaces of the bars **26***a* and **26***b* are contoured to form pole pieces **27** fitting the shape of the region defined by the coil **22**, hence placing the portion of the housing **14** between the protruding portion **20** in the gap of the magnetic circuit of the electromagnet.

The coil **22** is in the form of a copper strip, and, except for the portion **16** of the housing, it is spaced from and conforms to the periphery of the housing **14**. The coil **22** has a protruding portion **28** which extends into the protruding portion **16** of the housing. The coil **22** also has a radial lip **30** which extends between the protruding portion **28** and the annular portion of the coil **22**, and an aperture **32** is disposed in the lip **30** of the coil **22**, so that particles may pass from the outer orbit of the synchrocyclotron **10** through the aperture **32**. The lip **30** forms a magnetic shield between the two accelerators.

The synchrocyclotron **10** has a single "D" **36** disposed in the half of the housing **14** opposite to the lip **30**. A folded "D" **38** is disposed between the "D" **36** and the coil **22**, and a transmission line **40** extends from the "D's" **36** and **38** out of the housing **14**. The transmission line **40** is connected to a source **42** of frequency modulated radio frequency excitation. In like manner, a source **44** of direct current is connected to the coil **22**.

A deflector **46** is positioned downstream from the lip **30** of the coil **22** and is disposed adjacent to the coil **22**. The deflector **46** consists of two magnetic members **48** and **50**, the members **48** and **50** being secured to opposite sides of the housing **14** and having protruding ridges **52** in spaced confronting relationship generally aligned parallel to the outer orbit. The deflector **46** intensifies the magnetic field between the ridges **52** to displace the outer orbit of the cyclotron **10** and direct it through the aperture **32**.

The ring accelerator **12** surrounds the cyclotron **10**, and abuts the protruding portion **28** of the coil **22** of the cyclotron **10**. The ring accelerator **12** is disposed generally tangent to the synchrocyclotron **10**. The ring accelerator **12** has a circular orbit chamber **54** which is evacuated in a conventional manner. The orbit chamber **54** has a rectangular cross section, as illustrated in Fig. 5, and is provided with an inwardly protruding portion **56** which merges with and is sealed to the outwardly extending portion **16** of the housing **14**. Particles passing through the aperture **32** in the lip **30** of the coil **22** pass directly into the orbit chamber **54** of the ring accelerator **12**.

The ring accelerator **12** is provided with a magnetic field which traverses the orbit chamber **54** in a direction normal to the plane of the ring. This magnetic field is maintained by a plurality of electromagnets **60** which are disposed about essentially the entire orbit chamber **54**. Each of the electromagnets **60** has a C-shaped yoke **62** which curves longitudinally to conform to the curvature of the orbit chamber **54**. The yoke **62** abuts the orbit chamber **54**, and with the orbit chamber forms a channel **64** for an electrical coil **66**, and the coil **66** extends through the channel **64** about the ends of the yoke **62** and across the side of the yoke **62** opposite the channel **64**, as illustrated in Figure 5.

One or more cavity resonators **68** are disposed between a pair of adjacent electromagnets **60** to accelerate the particles revolving in the orbit chamber **54**. The resonator **68** is in the form of an electrically conducting plate. The resonator **68** extends through the wall of the orbit chamber **54** and is provided with an aperture **70** which permits the particles within the orbit chamber **54** to pass through the resonator. The resonator **68** is connected to a pulse source **72** which places a potential on the resonator to accelerate the particles. The pulse source **72** is synchronized with the source **42**, so that the pulses from the source **72** occur at the proper time.

An inflector **74** is disposed within the orbit chamber **54** confronting the lip **30** of the coil **22**. The inflector **74** is disposed adjacent to the inner edge of the magnet **60** and consists of a pair of magnetic members identical in construction to the members **48** and **50**. In like manner, the members are disposed in spaced confronting relation, and in addition are disposed between the poles of one of the electromagnets **60**.

Neither the synchrocyclotron nor the ring accelerator will be further described, since additional details are available in the published art. In addition, a suitable ring accelerator is disclosed in the patent application, Donald W. Kerst and Keith R. Symon, entitled "Imparting Energy to Charged Particles," S.N. 557,594, filed January 5, 1956.

The location and the strength of the deflector **46** in the synchrocyclotron **10**, and the location and strength of the inflector **74** in the ring accelerator **12** must be carefully selected relative to the distance from the lip **30**. The deflector **46** should be positioned at a distance from the axis of the cyclotron **10** slightly greater than the last equilibrium orbit thereof, and should be positioned downstream from the lip **30** by an angle ϕ between the radius of the lip **30** and the radius of the deflector **46** given by the following equation:

$$\tan \omega_x \phi = \frac{\sinh \sigma_x}{\sin 2\pi\omega_x + \frac{P}{2\omega_x}(1-\cos 2\pi\omega_x)}$$

where P is the strength of the deflector element given by the expression

$$P = -\frac{S}{2R}\frac{1}{H}\left(\frac{dH}{dR}\right)$$

in the deflector element and ω_x is the number of radial betatron oscillations per revolution of the particles. S is the azimuthal width of the deflector element, H is the

strength of the magnetic field in the magnet, and R is the radius of the machine. Also,

$$\frac{\omega o}{2\pi}$$

is the frequency of the ions, and $\omega_x=(\sqrt{1-n})\omega_o$ where

$$n=-\frac{R}{H}\frac{dH}{dR}$$

σ_x is defined by the expression:

$$\cosh \sigma_x=\cos 2\pi\omega_x+\frac{P}{2\omega_x}\sin 2\pi\omega_x$$

The deflector in the low energy accelerator and the inflector in the high energy accelerator both operate to increase the field at their respective areas, thereby creating a magnetic bump which shifts the orbit from its normal direction. In the case of the deflector **46**, the magnetic bump pushes the orbit inwardly from the equilibrium orbit, causing the charged particles to pass through the lip. In the case of the inflector **74**, the magnetic bump pulls the charged particles to displace their orbit into the high energy accelerator, thereby preventing the charged particles from striking a portion of the wall of the accelerator rather than following the orbit chamber **54**. Therefore, the equation above defines the location not only of the deflector **46**, but also of the inflector **74**, provided the ring accelerator **12** operates as a nonalternating gradient accelerator. However, when the high energy ring accelerator **12** is an alternating gradient type machine, as here disclosed, the angle ϕ' between the lip **30** and the inflector **74** relative to the axis of the ring accelerator **12** is given by the expression:

$$\tan(\nu_x\phi'+\delta_x)=\left[\frac{Q_x(1+\cos 2\pi\nu_x)-\sin 2\pi\nu_x}{Q_x(1-\cos 2\pi\nu_x)+\sin 2\pi\nu_x}\right]^{1/2}$$

where

$$Q_x=\frac{P}{2\mu_x}\sec\delta_x$$

ν_x is the number of radial betatron oscillations per revolution of the particles in the accelerator, and P is the strength of the inflector, as defined above. δ_x and μ_x are parameters yielding a measure of the scallop in the orbit of the particles and specifying the type of accelerator. In the special case of nonalternating gradient accelerators, such as the synchrocyclotron set forth above, $\mu_x=\omega_x$, and $\delta_x=0$, thus producing the special form equation set forth for the synchrocyclotron above. In the case of an alternating gradient ring accelerator, μ_x and δ_x assume values in the order of 10 to 100, which represent design criteria for the accelerator.

Throughout this disclosure, the deflector and inflector have been illustrated as single assemblies of confronting magnetic elements. However, it is to be understood that the inflector and deflector may be constructed with a plurality of assemblies of confronting elements also. For example, in the deflector **46** it may be desirable to place an assembly of elements on the upstream side of lip **30** in order to restore the orbits within the accelerator to their proper position relative to the axis of the accelerator. Also, it may be desirable under some circumstances to place an assembly of elements which operate to decrease the intensity of the magnetic field on the upstream side of the lip **30**.

The transfer mechanism for cascading accelerators is effective to transfer particles continuously or in pulses depending upon the method of operation of the low energy accelerator, here the synchrocyclotron **10**. Further, the transfer mechanism may be employed to transfer particles of any energy from one machine to another.

From the foregoing disclosure, those skilled in the art will readily devise many modifications and additions to the structure here disclosed. It is therefore intended that the scope of the present invention be not limited by the foregoing disclosure, but rather only by the appended claims.

What is claimed is:

1. A device for accelerating charged particles comprising, in combination, a first circular accelerator, a second circular accelerator having a portion thereof disposed essentially tangentially to the first circular accelerator, and means for transferring particles from the first accelerator to the second accelerator including a magnetic deflector in the first accelerator, a magnetic shield disposed between the accelerators, and a magnetic inflector in the second accelerator.

2. A device for accelerating charged particles comprising, in combination, a cyclotron, a ring accelerator having a portion disposed tangentially to the cyclotron, and means to transfer particles from the cyclotron to the ring accelerator including a magnetic deflector disposed within the cyclotron, a magnetic shield disposed between the ring accelerator and the cyclotron, and a magnetic inflector disposed within the ring accelerator.

3. A device for accelerating charged particles comprising, in combination, a cyclotron having an annular accelerating cavity with an outwardly protruding portion terminating in a radial lip, a ring accelerator having an annular orbit chamber with an inwardly protruding portion terminating in a radial lip, the ring accelerator being disposed essentially tangential to the cyclotron with the radial lip of the cyclotron confronting the radial lip of the ring accelerator, a radial magnetic shield disposed between the cyclotron and ring accelerator having an aperture for the passage of particles from the cyclotron to the ring accelerator, a deflector disposed on the downstream side of the shield within the magnetic field of the cyclotron and radially outwardly from the outermost orbit thereof, and an inflector disposed radially inwardly from the innermost orbit and within the magnetic field of the ring accelerator at the downstream side of the magnetic shield.

4. A device for accelerating charged particles comprising, in combination, a cyclotron having an annular accelerating cavity with an outwardly protruding portion terminating in a radial lip, a ring accelerator having an annular orbit chamber with an inwardly protruding portion terminating in a radial lip, the ring accelerator being disposed essentially tangential to the cyclotron with the radial lip of the cyclotron confronting the radial lip of the ring accelerator, a radial magnetic shield disposed between the cyclotron and ring accelerator having an aperture for the passage of particles from the cyclotron to the ring accelerator, a deflector disposed on the downstream side of the shield within the magnetic field of the cyclotron at a distance slightly greater than the diameter of the outermost orbit thereof and spaced from the shield by an angle ϕ relative to the axis of the cyclotron given by the expression:

$$\tan\omega_x\phi=\frac{\sinh\sigma_x}{\sin 2\pi\omega_x+\frac{P}{2\omega_x}(1-\cos 2\pi\omega_x)}$$

where ω_x is the number of radial betatron oscillations per revolution of particles in the cyclotron, σ_x is defined by the expression:

$$\cosh\sigma_x=\cos 2\pi\omega_x+\frac{P}{2\omega_x}\sin 2\pi\omega_x$$

and P is the strength of the deflector,

$$-\frac{S}{2RH}\frac{dH}{dR}$$

H being the magnetic field intensity, R being the radial distance of the deflector from the center of the cyclotron, and S being the azimuthal width of the deflector, and an inflector disposed radially inwardly from the innermost orbit and within the magnetic field of the ring accelerator at the downstream side of the magnetic shield by an

angle ϕ' relative to the center of the ring accelerator given by the expression:

$$\tan(\nu_x\phi'+\delta_x)=\left[\frac{Q_x(1+\cos 2\pi\nu_x)-\sin 2\pi\nu_x}{Q_x(1-\cos 2\pi\nu_x)+\sin 2\pi\nu_x}\right]^{1/2}$$

where ν_x is the number of radial betatron oscillations per revolution of the particles in the ring accelerator and Q_x is equal to

$$\frac{P}{2\mu_x}\sec\sigma_x$$

P being defined for the inflector as hereinbefore for the deflector, μ_x and σ_x being accelerator constants that assume values in the order of 10 to 100.

5. A device for accelerating charged particles comprising, in combination, a first circular accelerator, a second circular accelerator having a portion thereof disposed essentially tangentially to the first circular accelerator, and means for transferring particles from the first accelerator to the second accelerator including a magnetic deflector in the first accelerator, a magnetic shield disposed between the accelerators, and a magnetic inflector in the second accelerator, the deflector being disposed on the downstream side of the magnetic shield by an angle ϕ relative to the axis of the first accelerator given by the expression:

$$\tan(\nu_x\phi+\delta_x)=\left[\frac{Q_x(1+\cos 2\pi\nu_x)-\sin 2\pi\nu_x}{Q_x(1-\cos 2\pi\nu_x)+\sin 2\pi\nu_x}\right]^{1/2}$$

where ν_x is the number of radial betatron oscillations per revolution of the particles and Q_x is equal to

$$\frac{P}{2\mu_x}\sec\sigma_x$$

P being the strength of the deflector,

$$-\frac{S}{2RH}\frac{dH}{dR}$$

H being the magnetic field intensity, R being the radial distance of the deflector from the center of the first accelerator, S being the azimuthal width of the deflector, μ_x and σ_x being accelerator constants, and the inflector being disposed in the second accelerator on the downstream side of the magnetic shield by an angle relative to the axis of the second accelerator given by the above expression.

6. A device for accelerating charged particles comprising, in combination, a cyclotron having a cavity and an annular strip of electrically conducting material with an outwardly protruding portion and a radial lip extending therefrom, said lip having an aperture for passing particles and forming a magnetic shield, a ring accelerator disposed essentially tangentially to the cyclotron, said ring accelerator having an annular orbit chamber with an inwardly protruding portion confronting the radial lip of the cyclotron, a deflector disposed on the downstream side of the shield within the magnetic field of the cyclotron radially outwardly from the outermost orbit thereof at a distance slightly greater than the diameter of the outermost orbit thereof and spaced from the shield by an angle ϕ relative to the axis of the cyclotron given by the expression:

$$\tan\omega_x\phi=\frac{\sinh\sigma_x}{\sin 2\pi\omega_x+\frac{P}{2\omega_x}(1-\cos 2\pi\omega_x)}$$

where ω_x is the number of radial betatron oscillations per revolution of the particles in the cyclotron, σ_x is defined by the expression:

$$\cosh\sigma_x=\cos 2\pi\omega_x+\frac{P}{2\omega_x}\sin 2\pi\omega_x$$

and P is the strength of the deflector,

$$-\frac{S}{2RH}\frac{dH}{dR}$$

H being the magnetic field intensity, R being the radial distance of the deflector from the center of the cyclotron, and S being the azimuthal width of the deflector, and an inflector disposed radially inwardly from the innermost orbit and within the magnetic field of the ring accelerator at the downstream side of the electrostatic shield by an angle ϕ' relative to the center of the ring accelerator given by the expression:

$$\tan(\nu_x\phi'+\delta_x)=\left[\frac{Q_x(1+\cos 2\pi\nu_x)-\sin 2\pi\nu_x}{Q_x(1-\cos 2\pi\nu_x)+\sin 2\pi\nu_x}\right]^{1/2}$$

where ν_x is the number of radial betatron oscillations per revolution of the particles in the ring accelerator, Q_x is equal to $\frac{P}{2\mu_x}\sec\sigma_x$

P being defined as hereinbefore, and μ_x and σ_x being accelerator constants that assume values in the order of 10 to 100.

7. A device for accelerating charged particles comprising the elements of claim 2 wherein the ring accelerator is a fixed field alternating gradient accelerator.

References Cited in the file of this patent

UNITED STATES PATENTS

2,473,477	Smith	June 14, 1949
2,658,999	Farly	Nov. 10, 1953