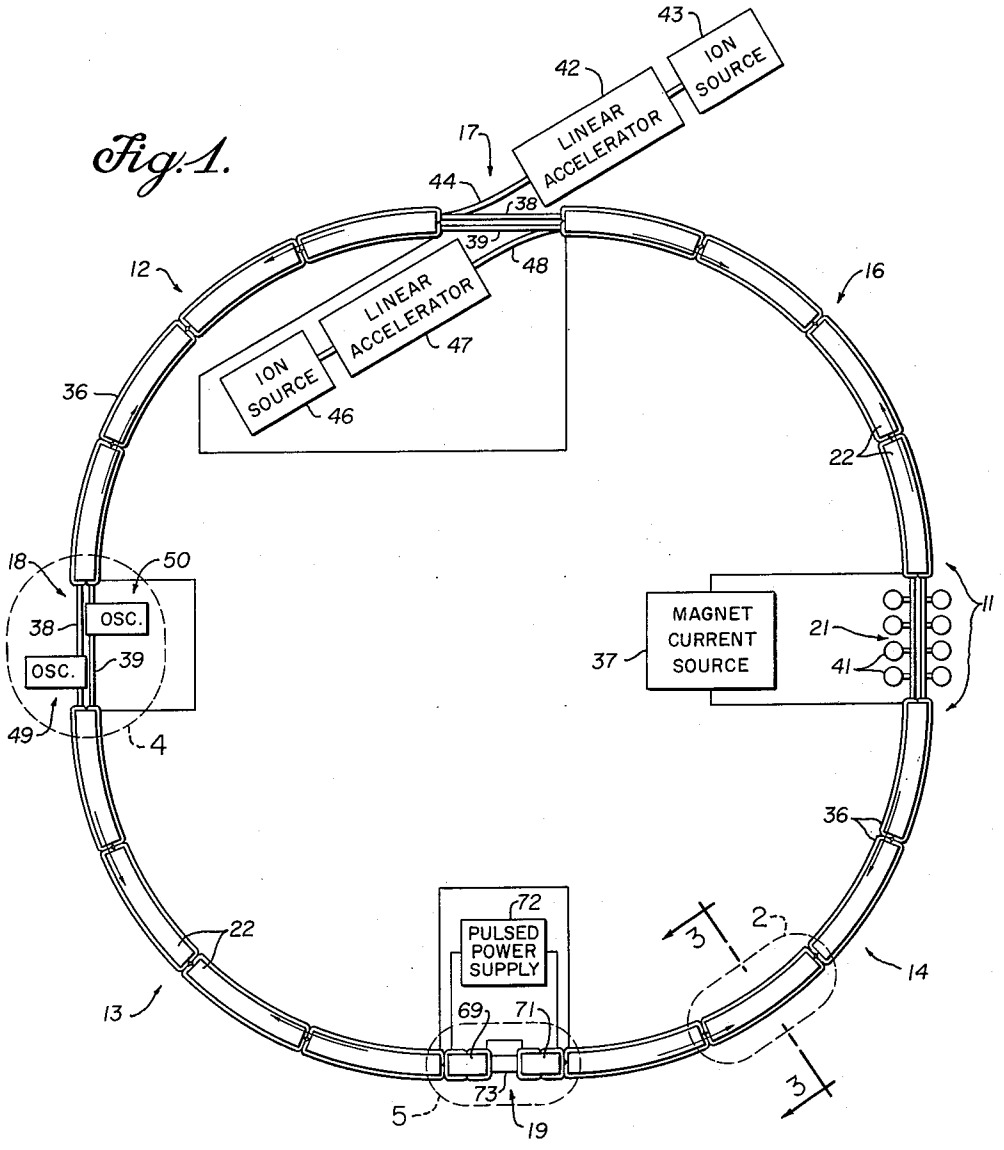
April 11, 1961 R. J. BURLEIGH 2,979,635

CLASHING BEAM PARTICLE ACCELERATOR

Filed July 15, 1959 3 Sheets-Sheet 1

Fig. 1.



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CLASHING BEAM PARTICLE ACCELERATOR

Filed July 15, 1959 3 Sheets-Sheet 2

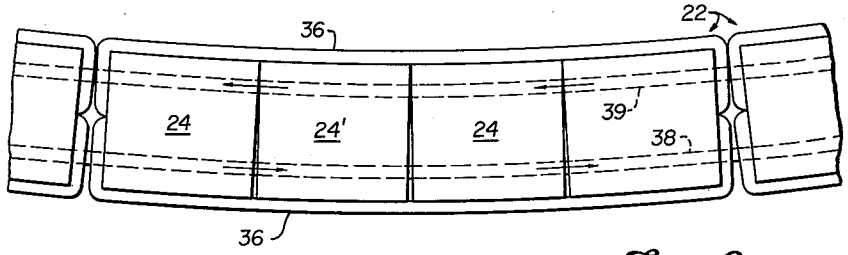


Fig. 2.

Fig. 4.

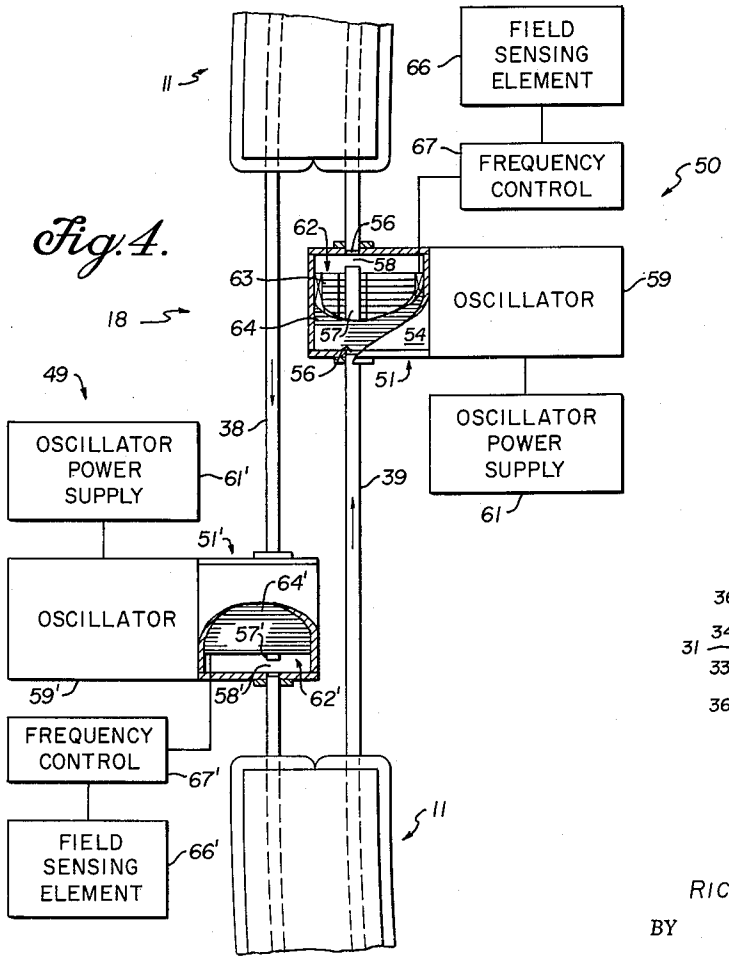
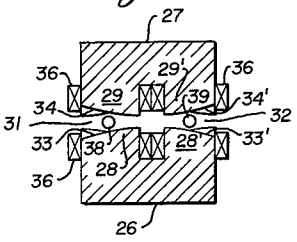


Fig. 3.



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CLASHING BEAM PARTICLE ACCELERATOR

Filed July 15, 1959 3 Sheets-Sheet 3

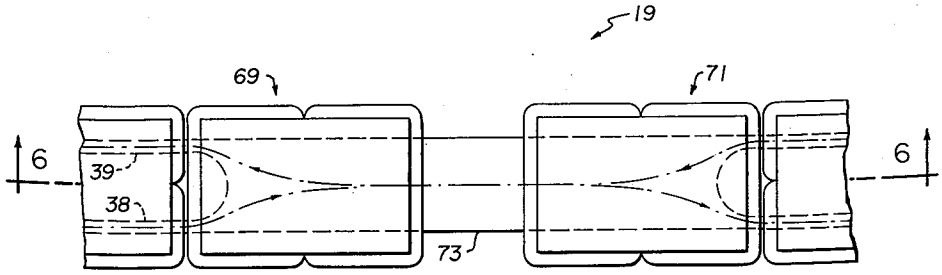


Fig. 5.

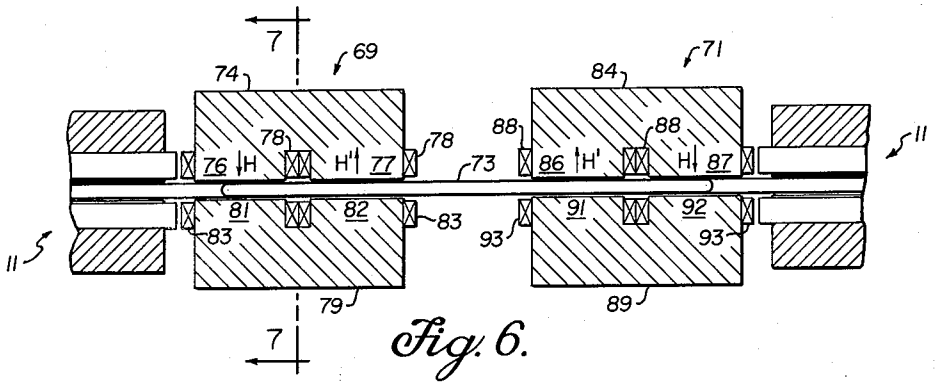


Fig. 6.

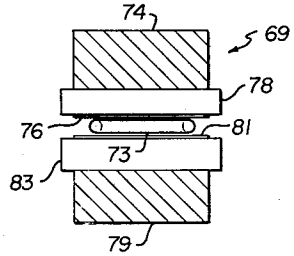


Fig. 7.

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United States Patent Office 2,979,635
Patented Apr. 11, 1961

2,979,635

CLASHING BEAM PARTICLE ACCELERATOR

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Filed July 15, 1959, Ser. No. 827,409

14 Claims. (Cl. 315—5.18)

This invention relates to apparatus for accelerating beams of charged particles and, more particularly, to an accelerator producing two oppositely directed particle beams and having provision for colliding the two beams to produce high energy nuclear interactions.

Cyclotrons, synchrotrons, and other existing forms of high energy charged particle accelerator have heretofore been designed to accelerate a single beam composed of particles having a substantially uniform circulatory direction, which beam is caused to impinge upon a stationary target for the purpose of inducing various types of interaction between the high energy particles and the target material. In the design of such machines, interest has centered on increasing final beam energy since the range of phenomena which can be studied is thereby correspondingly increased. Several difficult obstacles are encountered, however, in attempting to reach beam energies higher than that obtainable with existing equipment, i.e., in obtaining energies exceeding a few billion electron volts.

Using conventional design concepts, the cost of multi-bev. accelerators becomes excessive and the physical size of the apparatus must also be very large. In addition, operational problems with respect to obtaining sufficient beam intensity and beam stability become severe. The net result of these considerations is to make the attainment of extreme high energies a difficult and costly undertaking and a clear need exists for a fundamental new approach to the design of such accelerators.

In addition to the stated design and cost problems associated with the use of conventional techniques to achieve high energy, a further and extremely significant limitation exists on the effectiveness of the conventional accelerator for high energy studies. The effective energy of a moving particle, insofar as interaction with a stationary particle is concerned, is dependent upon the ratio of the mass of the moving particle to that of the stationary particle, the effect being a direct consequence of the conservation of energy and momentum. Assuming, for purposes of discussion, that the interactions are perfectly elastic, a complete transfer of energy from moving particle to stationary particle can take place only if the masses of the two particles are equal. If the masses of the particles are unequal, the energy transfer must be incomplete and moreover the discrepancy in energy transfer increases exponentially with respect to the mass imbalance. Thus doubling the energy of a moving particle does not double its effective energy with respect to a stationary particle provided a mass imbalance exists.

The significance of the foregoing effect in accelerator bombardments may be illustrated by considering the common practice of using protons as the accelerated particles and of utilizing hydrogen as the target material since the resultant interaction is essentially a bombardment of protons by protons. It may immediately be seen that the energy transfer in the interaction can never be complete since, owing to the relativistic mass increase experienced by a moving object, the bombarding proton will always

have a greater mass than the stationary target proton. Moreover since the mass of the bombarding proton increases exponentially with energy, the discrepancy between absolute particle energy and available particle energy becomes increasingly severe as accelerators are made larger. The specified effect therefore seriously reduces the experimental usefulness of very large accelerators which are constructed in accordance with conventional design concepts.

To illustrate the severity of this limitation, it may be shown that a proton accelerated to 6 bev. has an effective interaction energy of only 1.968 bev. with respect to a stationary target proton, the controlling relationship being:

$$(W)^2=(m_1)^2+(m_2)^2+2m_1E_2^1$$

where:

W=total energy, including all rest masses, available in the center of mass system,
m_1=rest mass of the stationary target particle,
m_2=rest mass of the accelerated particle,
E_2^1=total energy in the laboratory system of the accelerated particle including the rest mass thereof.

From the above relationship the effective energy of a 500 bev. proton striking a stationary proton may be shown to be only 28.809 bev. and thus the gains from going to extraordinarily high energies, assuming such to be technically feasible, are proportionately slight. Increasing the output energy of conventional accelerators thus gives a diminishing return and an energy level presumably exists where the slight increase in effective energy to be gained fails to justify the extreme expense of achieving it.

As a new and economical approach to accelerator design and particularly as a means of overcoming the foregoing effective energy limitation, it has been suggested that the desired particle interactions be produced by colliding two oppositely directed similar high energy particle beams. Under these conditions, the colliding particles are each traveling at the same velocity and their masses are therefore equated. Owing to the lack of any mass imbalance, the energy available for interaction is essentially the sum of the energies of the two particles and the energy limitation hereinbefore discussed is overcome. By eliminating the discrepancy between real energy and available energy, the resultant particle interactions are equivalent to those produced by a conventional accelerator having a beam energy far exceeding the sum of the energies of the colliding beams. Using the relationship hereinbefore given, the interaction energy available through the collision of two 6.15 bev. proton beams will be found to equal that available in the collision of a 100 bev. proton with a stationary proton.

Thus while the construction of a conventional accelerator to produce a 100 bev. proton beam will pose formidable problems, effectively the same results can be achieved by colliding two beams each of which has an energy of only 6.15 bev. which latter energy has been achieved with existing equipment of conventional design.

The use of colliding or clashing beams is therefore a highly advantageous technique for achieving extremely high energy particle interactions. Considering now specific means with which the collision of particle beams can be effected, it has been proposed that two circular accelerators of the proton synchrotron class be utilized, the two beams of which rotate in opposite senses. The two accelerators were to be disposed in a tangential relationship, i.e., with a single common point on the orbits of each, such that the beams may be clashed at the common point in the orbits to produce the desired reactions. While the accelerators might conceivably be spaced apart and the beam of each extracted for collision

at some intermediate point, the difficulties associated with extracting a sufficient proportion of the beam from accelerators of this type would make this configuration a much less effective one.

As an alternate method, it has been proposed that a single accelerator be used together with a beam storage means disposed adjacent the accelerator. In this system a beam is accelerated in a first rotational sense and transferred to the storage means. Subsequently a second beam is accelerated with a reverse rotational sense and collided with the first, or stored, beam. Inasmuch as the storage means is an annular magnet structure somewhat similar to that of the accelerator, this method of colliding beams is only slightly less costly, and physically about as large, as the two accelerator method. In addition, the duty cycle must be less than one half that of the two accelerator method since a collision can at best be effected only on alternate pulses of the accelerator magnet.

Thus while the clashing beam concept presents an excellent method for achieving high energy reactions, the apparatus as heretofore envisioned requires large quantities of costly equipment and space.

The present invention provides a more economical, compact, and efficient clashing beam accelerator with which extreme high energy particle interactions can be readily accomplished. Specifically the invention utilizes a single annular magnet structure within which two concentric contra-rotating ion beams are accelerated, one beam orbit being of slightly less diameter than the other. At one section of the magnet deflector means are provided which deflect the inner beam to a greater orbital radius while simultaneously deflecting the outer beam to a lesser radius thus causing the two beams to collide head on. A further property of the deflecting means is to return those particles which do not undergo collision to the original orbits so that the particles re-circulate within the accelerator with the possibility of producing interactions on subsequent turns.

By means of the foregoing unique structure, particle interactions at energies far greater than those heretofore artificially produced can be effected with an accelerator mechanism not appreciably more costly or larger than conventional accelerators of comparatively low effective energy.

It is accordingly an object of this invention to provide an improved means for inducing high energy interactions between particles.

It is another object of this invention to provide a charged particle accelerator capable of achieving nuclear interactions at far higher effective energies than have heretofore been possible.

It is an object of this invention to provide a clashing beam particle accelerator of comparatively economical cost and small size with respect to earlier designs.

It is still a further object of the present invention to provide a compact efficient accelerator for colliding oppositely directed high energy charged particle beams.

It is an object of the invention to provide a clashing beam charged particle accelerator requiring only a single annular magnet structure.

It is an additional object of this invention to provide a charged particle accelerator for colliding oppositely directed particle beams to produce interactions therebetween and in which the region of beam collision is relatively free from obstruction whereby the interactions may be more conveniently and completely studied.

It is still a further object of this invention to provide a particle accelerator having provision for establishing two concentric contra-rotating particle beams and having means for deflecting the beams to achieve a collision therebetween and for returning the beams to the original orbits thereof for recirculation within the accelerator.

The invention, together with further objects and advantages thereof, will best be understood by reference to

the following specification together with the accompanying drawings, of which:

Figure 1 is a plan view of an accelerator and appurtenances with certain conventional components thereof being shown in block form;

Figure 2 is an enlarged view of the portion of Figure 1 encircled by the dashed line 2 thereon and showing a typical segment of the principal magnet of the acceleratr;

Figure 3 is an enlarged cross section view taken along 3—3 of Figure 1 and showing internal details of the principal magnet;

Figure 4 is an enlarged plan view of the portion of Figure 1 encircled by dashed line 4 thereon and showing the beam accelerating region of the accelerator together with components, shown in block form, for providing radio-frequency excitation thereto;

Figure 5 is an enlarged plan view of the portion of Figure 1 encircled by dashed line 5 thereon and showing the beam clashing section of the accelerator;

Figure 6 is a section view taken along line 6—6 of Figure 5 further illustrating the beam clashing region of the accelerator; and

Figure 7 is a cross section view taken along line 7—7 of Figure 6.

Referring now to the drawing and more particularly to Figure 1, the general configuration of the accelerator will be described, the detailed structure of the various component parts thereof being hereinafter described with reference to later figures.

The accelerator comprises an annular electro-magnet structure **11** segmented into four separate quadrant sectors **12, 13, 14,** and **16** the quadrants being spaced apart a small distance to provide straight sections **17, 18, 19,** and **21** on the particle orbits which sections are utilized for such operations as beam injection, acceleration, and beam collision. The described construction of a large accelerator magnet in spaced quadrants is a conventional practice well understood within the art, and it should be observed that the resultant distortion of the beam orbits from exact circularity, occasioned by the presence of the straight sections **17, 18, 19,** and **21,** does not deleteriously affect the beam dynamics and the presence of such sections may be disregarded insofar as the analysis of interactions between charged particles and the field of the magnet is concerned.

For convenience in construction, to facilitate adjustment, and to expedite the replacement of defective or damaged components, each of the magnet quadrants **12, 13, 14,** and **16** is in turn formed of four discrete sections **22,** each of which sections is provided with separate windings as will hereinafter be described. It should be understood that the construction of the magnet quadrants in sections **22** is a convenience rather than a necessity and that various numbers of sections per quadrant can be used if desired.

Referring now to Figures 2 and 3, the magnet sections **22** are in turn each formed of four sub-sections **24,** alternate ones of the sub-sections being designated by the numeral **24'**. As shown in Figure 3 in particular, each sub-section **24** and **24'** comprises a lower portion **26** of U-shaped cross section and a similar but inverted upper portion **27,** the upwardly extending arms **28** of the lower portion being spaced a small distance from the downwardly extending arms **29** of the upper portion. Two magnet gaps **31** and **32** are thus formed, gap **32** being radially innermost with respect to the overall curvature of the magnet structure. To provide a strong focussing action on particle beams circulating within the magnet gaps **31** and **32,** the pole tips **33** and **34** of magnet arms **28** and **29** respectively are curved so that the gaps **31** and **32** are of exponentially increasing height outward from a midpoint between the two gaps. Methods for calculating the precise curvature of pole tips **33** and **34** to achieve the desired strong or alternating gradient, focussing action in a particular system are well under-

stood and may be studied by reference to U.S. Patent No. 2,736,799 entitled Focussing System for Ions and Electrons and issued to Nicholas Christofilos, February 28, 1956. It will be noted that to achieve this form of beam focussing, the curvature of the pole faces 33 and 34 on the alternate sub-sections 24' must be reversed from that of the intervening sub-sections 24, the gaps between the pole faces of the alternate sub-section 24' being of decreasing height outward from the midpoint of the magnet structures. It will be understood that other forms of beam focussing may be employed with the accelerator if desired and in utilizing certain of the various known forms of focussing, the curvature of all pole tips may be the same.

Each of the magnet sections 22 utilizes four windings 36, one encircling a first set of arms 28 of each of the four sub-sections 24, one encircling the opposite set of arms 28', and the remaining two being correspondingly placed on the upper magnet portions 27. As shown in Figure 1, all the magnet windings 36 of each of the four magnet quadrants are connected in series relationship and are excited by a suitable source 37 of pulsed direct current.

With respect to the design of the magnet 11, it will be found advantageous if the two particle beams have exactly the same energy at the time of collision. Therefore, since the radius of the inner orbit is less than that of the outer orbit, the magnetic field across the inner orbit must be proportionately stronger than that across the outer orbit if beams of equal energy are to be contained. This is accomplished by proportioning the particular pole pieces 33' and 34' which are associated with the inner orbit to be of less lateral width than the poles at the outer orbit thereby concentrating the flux across the inner gap 32. Alternately an iron shunt across the outer gap 31 may be employed to reduce the relative flux thereacross.

Referring now to Figures 1 and 3, two annular vacuum envelopes are disposed within the magnet structure, a first such envelope 38 being centered within the outermost magnet gap 31 and the second envelope 39 being within the inner gap 32 and therefore being of a slightly lesser diameter. Each of the vacuum envelopes 38 and 39 conform to the magnet structure in having four spaced apart quadrant sections joined by straight sections and each envelope is of circular cross-section except at specialized points as will hereinafter be described. It will be apparent that a single large vacuum tank encompassing both particle orbits might be utilized if desired, the use of two separate envelopes as described above being advantageous from the standpoint of reducing the volume which must be pumped to high vacuum. Considering now means for evacuating the envelopes 38 and 39, two banks of diffusion pumps 41 are situated in one of the magnet straight sections 21, one half of the pumps being connected with the outer envelope 38 and the others being connected with the inner envelope 39. If space limitations permit the arrangement, it may be found preferable to distribute the pumps around the two envelopes as the pumping speed will be thereby enhanced.

Considering now provision for the injection of charged particles into the two beam orbits within the two vacuum envelopes 38 and 39, it is a characteristic of accelerators of the proton synchrotron class that particles must be injected into the beam orbit with an appreciable initial energy and thus a smaller accelerator must be utilized as a pre-accelerator. As shown in Figure 1, a first linear accelerator 42, which may be of the type disclosed in U.S. Patent 2,545,595 issued to Luis W. Alvarez March 20, 1951, and entitled Linear Accelerator, and which is provided with an ion source 43, is positioned adjacent the magnet straight section 17 and outside the area enclosed by the magnet. The linear accelerator 42 is positioned to emit high energy particles along an axis transecting the outer vacuum envelope 38 at an acute angle. Inasmuch as the bulk of the magnet structure will generally prevent the axis of accelerator 42 from being aligned tangentially with respect to the beam orbit within the envelope 38, an arcuate electrostatic beam deflector 44 is provided to bend the beam from linear accelerator 42 into colinearity with the beam orbit of the envelope, the deflector being hermetically sealed and evacuated by communication with the vacuum regions of the envelope and the accelerator 42.

To inject charged particles into the inner beam orbit, i.e., into vacuum envelope 39, a second similar ion source 46 and linear accelerator 47 are disposed adjacent the magnet straight section 17 within the area encircled by the magnet structure. Such second linear accelerator 47 is positioned to emit a beam towards the vacuum envelope 39 at an acute angle thereto and opposite to the direction of the beam from the first linear accelerator 42, a second vacuum tight arcuate beam deflector 48 being provided to bend the beam into colinearity with the axis of the envelope. Thus the beams which are injected into the two orbits of the magnet 11 are oppositely directed, the beam in the outer envelope 38 being of a counter-clockwise rotational sense in this instance and the beam in the inner envelope 39 being of a clockwise rotational sense. It will be understood, however, that other means for establishing the contra-rotating orbits are feasible. A single linear accelerator may be used to inject particles into both orbits, for example, a suitable reversing field beam steering magnet being utilized to deflect particles alternately into the outer orbit and into the inner orbit.

Particles injected into the two beam orbits within the magnet 11 during the pulsing thereof will circulate around the axes of two vacuum envelopes 39 and 38 provided the field of the magnet at the time of injection is properly matched to the particle energy, mass, charge and orbit radius in accordance with the well-known relationships governing such orbits. Considering now means by which the particles are further accelerated as the magnet field increases thereby maintaining a substantially constant orbit, a first and second accelerating system 49 and 50 respectively are disposed at the magnet straight section 18, the first system 49 being operative on the outer beam orbit and the second system 50 acting on the inner orbit.

Referring now to Figure 4, the region of the accelerator adjacent straight section 18 is shown in more detail, together with the component members and associated circuitry of the accelerating systems 49 and 50. Except insofar as two separate accelerating systems are utilized, the beam accelerating components of the invention make use of conventional design concepts, well understood within the art, and accordingly certain elements of the electrical circuitry are shown in block form. Considering first the inner orbit RF system 50, to which the outer orbit system 49 is similar, a re-entrant cavity resonator 51 is positioned around a gap in the straight section of vacuum envelope 39. The resonator 51 comprises a cylindrical outer shell 54 having opposed end openings 56 into which the ends of the vacuum envelope 39 are fitted and secured so that the shell is effectively an enlarged segment of the envelope. To provide adequate space for a saturable reactor which will be hereinafter described, the openings 56, and thus the beam orbit through the resonator, is off-center with respect to shell 54 the major volume of the shell being towards the inside of the magnet 11. A cylindrical re-entrant section 57, having slightly less length and considerably less diameter than the shell 54, is disposed within the resonator coaxially with respect to the openings 56. The re-entrant section 57 is disposed with one end in contact with one endwall of the shell so that the opposite end of the section is spaced a small distance from the opening 56 in the shell forming an accelerating gap 58. It will be understood that both the shell 54 and re-entrant sec-

tion 57 are formed of electrically conductive material and are vacuum tight.

To establish the necessary alternating electrical field across the accelerating gap 58, the resonator 51 is energized by a cavity tuned RF oscillator 59 which is in turn provided with a suitable power supply 61. Thus, if the resonant frequency of resonator 51 is matched to the period of revolution of particles within the accelerator orbit, the particles may be made to cross the gap 58 once each RF cycle and at a phase therewith whereby the particles receive an increment of energy from the field across the gap. It is apparent, however, that as the particles are accelerated the period of revolution decreases and accordingly the frequency of resonator 51 must be correspondingly increased to maintain the necessary phase relationship.

As has been previously discussed, the field of magnet 11 also increases as the particles are accelerated thus holding the particles in a substantially constant orbit. Therefore control of the accelerating system frequency can be conveniently effected by obtaining a signal indicative of the instantaneous value of the magnetic field and utilizing such signal to control the frequency of the resonator 51. As a means for varying the frequency of the resonator 51, a saturable reactor 62 is disposed within the outer resonator shell 54. The reactor 62 comprises a cylindrical ferrite core 63 having an off-center longitudinal passage through which the re-entrant section 57 passes and having a winding 64 through which a current may be passed to vary the inductance of the reactor. Such change of inductance produces a corresponding change in the operating frequency of the oscillator resonator system and therefore serves to match the frequency of the electric field across gap 58 with the decreasing period of revolution of particles within the accelerator. To control the saturable reactor 62, and thus to control the operating frequency of the system, a suitable magnetic field sensing element 66 is positioned adjacent the magnet 11 and serves to deliver a signal indicative of the instantaneous value of the magnetic field to a reactor inductance control unit 67. The control 67 varies the energization of reactor windings 64 in accordance with the changing signal from sensing element 66, the particular level and rate of change of such energization being dependent upon the specific parameters of a given accelerator.

To provide for the acceleration of particles in the outer orbit, a second oscillator resonator system is provided which system is similar to that described but which operates through a slightly lower frequency range owing to the slightly greater period of revolution of particles in the outer orbit. The duplicate system comprises a second cylindrical re-entrant resonator 51′ positioned in a gap in the straight section 18 of outer vacuum envelope 38, and forming an enlarged segment thereof. As in the previous instance, resonator 51′ is provided with a cylindrical re-entrant section 57′ centered on the axis of the vacuum envelope 38 and terminated short of one end of the resonator to form an accelerating gap 58′. A ferrite saturable reactor 62′ is disposed within the resonator 51′ and is provided with windings 64′ for controllably varying the inductance of the reactor. An oscillator 59′, with power supply 61′ is utilized to energize the resonator 51′ and the resonant frequency of the system is determined by a magnet field sensing element 66′ coupled to a reactor winding current control 67′.

By means of the described duplicate accelerating systems, the oppositely directed charged particle beams within the two vacuum envelopes 38 and 39 are each accelerated to high energy, the increasing field of the magnet 11 serving to hold the particles in a substantially constant orbit. When the desired energy level has been reached, and with reference to Figure 1, collision of the two beams is effected by a deflector magnet system situated at the accelerator straight section 19, such system comprising spaced apart deflector magnets 69 and 71 energized by a pulsed power supply 72.

Referring now to Figures 5, 6, and 7, elements of the beam clashing system at straight section 19 are shown in more detail, the deflector magnets 69 and 71 being shown disposed one at each end of the straight section and with a substantial spacing between the two magnets. The vacuum envelopes 38 and 39 are merged together substantially throughout the length of the straight section to form a single broad vacuum tank 73 having a lateral width exceeding the separation of the two beam orbits.

Considering now the structure of the deflector magnet 69 the magnet is comprised of an upper section 74 disposed above tank 73 and provided with two pole pieces 76 and 77 which are spaced along the upper surface of the tank, pole 76 being closest to the accelerator magnet 11. Each such pole piece is encircled by a separate winding 78. Directly beneath the upper section 74 is a similar but inverted lower section 79 having upwardly facing pole pieces 81 and 82 on the opposite side of tank 73 from pole pieces 76 and 77, respectively. Encircling each of the lower pole pieces 81 and 82 is a separate winding 83.

The second deflector magnet 71 is of similar design, comprising an upper section 84 with pole pieces 86 and 87 encircled by separate windings 88 and a similar but inverted lower section 89 having upwardly facing pole pieces 91 and 82 energized by separate windings 93, the pole pieces 87 and 92 being nearest the magnet 11.

The relative polarities of the pole pieces, and thus the manner of electrical connection between the various pole piece windings, of the deflector magnets 69 and 71, are determined by the requirement that the two particle beams be brought to a common intermediate radial position at the center of straight section 19 and then diverged to return to the original orbits. The necessary polarities to accomplish this are dependent upon the charge and rotational direction of the two particle beams and the general relationship is that the first of the deflector magnet fields encountered by the oncoming beam in the outer orbit should be of like polarity to the main accelerator magnet 11 in the outer orbit, the second and the third of the deflector fields traversed by the outer beam should be of opposite polarity and the last deflector magnet field to be traversed by the said outer beam should again have a polarity similar to that of the main accelerator magnet 11 at the outer orbit thereof. With appropriate field intensities, the effect of this sequence of fields is to first curve the outer beam inward towards the center of the accelerator and then to straighten the beam out along a trajectory coincident with the centerline of the vacuum tank 73 and subsequently to curve the beam outward again and then to redirect it along the outer orbit of the main accelerator magnet. It will be observed that the effect of this same sequence of fields on the inner orbit beam is to first deflect the beam outward and then to straighten the beam out along the centerline of tank 73 where it is coincident with, and oppositely directed to, the outer beam thereby effecting the desired particle collisions. Subsequently, the inner beam is deflected inward and then curved to return to the inner beam orbit of the main accelerator magnet 11.

Referring now to Figure 6 in particular, a specific example of suitable deflector magnet polarities is shown, the beams being assumed to be positively charged particles and to be circulating counter-clockwise in the outer orbit and clockwise in the inner orbit. Under these conditions, the magnetic field of the main accelerator magnet 11 must, in the region of the outer orbit, be directed downward and must be directed upward in the region of the inner orbit. Thus in accordance with the foregoing generalized rule, the field between pole faces 76 and 81 and the field between pole faces 87 and 92 must be directed downward as indicated by lines H and

the field between pole faces 77 and 82 and that between pole faces 86 and 91 must be directed upward as indicated by lines H'. It will be understood that variations in the described magnet polarity are possible, for example all polarities including that of the main magnet 11 may be reversed and satisfactory operation effected if each charged particle beam is injected into the accelerator with a reversed rotational sense. It will further be understood that the absolute field strengths between the specified sets of pole faces must be carefully adjusted relative to the field of the main magnets to achieve the desired radial displacement of each beam so that collision occurs.

In operation, and with reference to Figure 1 in particular, the preaccelerator systems are energized to inject particles into the two beam orbits defined by the vacuum tanks 38 and 39 and the main magnet current source 37 is pulsed on to confine the particles to the desired circular orbits. The particles are accelerated and bunched by the alternating field across the gaps 58 and 58' in resonators 51 and 51', the frequency of alternation of the field being continually increased concurrent with increase of the magnetic field through the hereinbefore described action of the saturable reactors 62 and 62'. When the two particle beams have been brought up to the desired energy, the deflector magnet power supply 72 is pulsed resulting in the outer beam being deflected inward in straight section 19 and in the inner beam being directed outward. During the interval that the field of the deflector magnets 69 and 71 is in the process of rising to the maximum value, the amount of radial excursion of the two beams is found to be less than that needed to effect beam collision. Since however, the deflector magnets act to return each beam to its proper orbit at the end of the straight section 19, the presence of the partial field in the deflector magnets during the specified interval does not significantly disturb the circulating beams. When the deflector magnet fields have risen to the maximum value, the radial excursion of each beam is such that the two beams are each colinear with the centerline of the straight section vacuum tank 73, and traveling in opposed directions, so that the desired interactions between component particles of the two beams is achieved. Such particles as do not undergo interactions are still returned to their proper orbit and recirculate with the possibility of undergoing interactions on subsequent turns.

In comparison with the target region of most conventional accelerators, a desirable characteristic of the deflector magnets and associated structure within the beam clashing straight section 19 is that the region surrounding the center of the vacuum tank 73, in which the desired beam collisions occur, is largely free from obstruction and thus the various detection instruments customarily used for the analysis of nuclear events may be readily placed at any of various positions.

Variations in portions of the described structure are possible and will suggest themselves to those skilled in the art. In the deflector magnet system at straight section 19, for example, a sequence of only three magnetic fields may be employed, in place of the four herein described, the two outer fields being of one polarity and the middle field being of reverse polarity. With the three field system the beam collision occurs only at one point rather than along an extended line and is thus advantageous from the standpoint of fixing the exact position of the detected nuclear event but has the disadvantages of lessened probability of particle interaction, partial obstruction of the particle interaction zone by the middle magnet structure, and deflection of charged secondary particles by the field of the magnet. Other possible variations in the structure include the provision of a second duplicate beam clashing system at another of the accelerator straight sections as, for example, at straight section 21, the probability of effecting the desired nuclear interactions with beams of given magnitude being thereby increased.

Thus 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 it is not intended to limit the invention except as defined in the following claims.

What is claimed is:

1. In a charged particle accelerator, the combination comprising an annular magnet structure establishing a first closed curvilinear beam orbit and establishing a second closed curvilinear beam orbit which is coplanar and concentric with said first orbit and which is of less diameter, charged particle injector means injecting particles into said first orbit for circulation therein in a first rotational direction and injecting particles into said second orbit for circulation therein in an opposite rotational direction, and at least one magnetic field producing means separate from said annular magnet structure, said field producing means being positioned on said orbits and establishing a field transecting said orbits whereby particles circulating in each of said orbits are converged and caused to collide.

2. In a charged particle accelerator, the combination comprising an annular magnet characterized by a first field region establishing a closed curvilinear outer beam orbit and further characterized by a second field region of reverse polarity with respect to said first region and establishing a closed curvilinear inner beam orbit which is concentric and coplanar with said first orbit and which is of lesser diameter, means injecting charged particles into said outer orbit for rotation therein in a first angular direction and injecting charged particles into said inner orbit for rotation therein in a reverse angular direction, and at least one magnetic field generating element positioned to straddle said inner and outer orbits at a selected azimuthal portion thereof and having a deflector field transecting each of said orbits which deflector field is of like polarity to said first field of said annular magnet, whereby particles in said outer orbit are curved inwardly and particles in said inner orbit are curved outwardly and collisions between said particles may be effected.

3. In a charged particle accelerator, the combination comprising a ring magnet having first and second field regions of opposite polarity defining two concentric coplanar substantially circular beam orbits, a first of said orbits being of greater diameter than a second of said orbits, means injecting charged particles into said first field region for circulation in said first orbit, means injecting charged particles into said second orbit for circulation therein in a rotational direction opposite to that of particles in said first orbit, and a plurality of deflector magnets positioned along a portion of said orbits each straddling said orbits and each establishing a magnetic field substantially normal to each of said orbits, the two terminal ones of said deflector magnets having a polarity similar to that of said first field region and at least one central one of said magnets having a polarity similar to that of said second field region whereby particles in each of said orbits are converged to a common trajectory at least one point and are subsequently returned to said orbits.

4. A charged particle accelerator substantially as described in claim 3 wherein said deflector magnets are four in number and each of the two central ones of said magnets have a polarity similar to that of said second field region.

5. A clashing beam charged particle accelerator comprising, in combination, an annular electromagnet characterized by two annular flux gaps for the containment of contra-rotating charged particle beams which gaps are concentric and a first of which is of greater diameter than the second, means for directing charged particles

into each of said flux gaps for rotation therearound in opposed angular directions to establish said contra-rotating beams, means for applying an alternating electrical field along a portion of each said flux gap for accelerating said particles therein, and a magnetic deflector having at least three field regions traversed by each of said contra-rotating charged particle beams, two spaced apart ones of said field regions having a polarity similar to that of said first flux gap of said electromagnet and an intermediate one of said field regions having a polarity similar to that of said second flux gap of said electromagnet whereby said contra-rotating beams are caused to converge at one portion of the orbits of said beams and to subsequently diverge for recirculation in said orbits.

6. A clashing beam charged particle accelerator substantially as described in claim 5 and wherein said two flux gaps of said annular electromagnet are of opposite polarity and said means for directing charged particles into each of said flux gaps injects like particles into each of said gaps.

7. A clashing beam charged particle accelerator comprising, in combination, an electromagnet having two concentric rings of spaced apart pole pairs for establishing two concentric annular flux gaps of opposed magnetic polarity which gaps define two concentric coplanar particle beam orbits, a pulsed electrical power source connected to energize said electromagnet, means injecting charged particles into a first of said orbits with a clockwise rotational direction therein and injecting charged particles into a second of said orbits with a counterclockwise rotational direction therein, a first electrical oscillator applying an alternating electrical field along a portion of said first orbit said oscillator having an operating frequency which increases as the field of said electromagnet increases, a second electrical oscillator applying alternating electrical field along a portion of said second orbit which oscillator has an operating frequency which increases as the field of said electromagnet increases, and a pulsed deflector magnet having at least one pair of spaced apart magnet poles which poles are disposed one each side of a selected portion of said orbits whereby a field transecting said orbits is established and particles in each of said orbits may be caused to converge.

8. A clashing beam accelerator substantially as described in claim 7 wherein said deflector magnet is electrically connected with said pulsed electrical current source and is pulsed concurrently with said electromagnet.

9. A clashing beam particle accelerator substantially as described in claim 7 and comprising the further combination of a second pulsed electrical power supply connected to energize said deflector magnet independently of energization of said electromagnet.

10. Apparatus for accelerating and colliding oppositely directed charged particle beams comprising, in combination, a vacuum envelope enclosing two concentric coplanar charged particle orbits a first of which orbits is of greater diameter than the second, a plurality of magnet pole pairs distributed around each of said orbits, one pole of each pair thereof being on each side of the associated orbit to establish a magnetic flux transecting said orbit, a pulsed current source connected in energizing relationship with said magnet poles to provide for oppositely directed magnetic fields across said orbits, a charged particle injector supplying particles to said first orbit for circulation therearound with a first rotational direction, a charged particle injector supplying particles to said second orbit for circulation therearound in an opposed rotational direction, a first variable frequency oscillator applying an alternating field along a section of said first orbit for accelerating particles circulating therein, said first oscillator being synchronized with said pulsed current source to oscillate at an increasing frequency as said flux across said orbit increases, a second variable frequency oscillator applying an alternating field along a section of said second orbit, said second oscillator being synchronized with said pulsed current source to oscillate at an increasing frequency as the flux across said orbit increases and to oscillate at a frequency exceeding that of said first oscillator, and a deflector magnet structure having a plurality of spaced apart pole pairs forming a plurality of magnetic flux gaps each traversed by each of said orbits, at least one central one of said flux gaps having a field direction similar to that associated with said second orbit and at least one of said flux gaps on each side of said central one of said flux gaps having a field direction similar to that associated with said first orbit, whereby contra-rotating particles in said two orbits are caused to converge in said deflector magnet structure and to subsequently diverge and return to said orbits.

11. Apparatus for accelerating and colliding oppositely directed charged particle beams substantially as described in claim 10 wherein said magnet pole pairs of said deflector magnet structure are at least four in number and the two central ones thereof are separated by a substantial field free gap whereby a beam colliding region is provided which region is substantially free from obstruction by surrounding magnet structures thereby enabling detection instruments to be readily placed therearound.

12. A charged particle beam accelerator providing for the colliding of oppositely directed charged particle beams comprising, in combination, a vacuum envelope enclosing two closed concentric and coplanar charged particle beam orbits which orbits are characterized by arcuate portions interposed with linear portions and a first of which orbits is of greater radius than the second, an electromagnet formed of a plurality of pole pairs distributed around said arcuate portions of each of said orbits, one pole of each said pair thereof being on each side of the plane of the associated orbit to provide a flux transecting said orbits at the arcuate portions thereof, a source of pulsed current connected to energize said electromagnet and to provide magnetic fields of opposite polarity across said orbits, means injecting like charged particles into each of said orbits for circulation therein in contra-rotating relationship, a pair of variable frequency oscillators one associated with each of said orbits and each having an accelerating electrode positioned adjacent the associated orbit to provide an alternating electrical field therealong, said oscillators being synchronously energized with said electromagnet to provide for an increasing frequency of oscillation as the field of said electromagnet increases, and a pulsed beam converging deflector magnet disposed along one of said linear sections of said orbits and having four pairs of spaced apart poles between which poles said orbits pass, the two outer ones of said pole pairs having a polarity corresponding to that of the principle electromagnet poles associated with said first orbit and the two central ones of said deflector magnet pole pairs having a reverse polarity whereby particles circulating in said two orbits are caused to converge for collision and particles not undergoing collision are returned to the original orbits for recirculation therein.

13. A deflector magnet structure for effecting the collision of two oppositely directed beams of similar charged particles which beams are separate and substantially parallel comprising, in combination, at least four pairs of electromagnet poles disposed along said two beams, the two poles forming each pair being spaced apart with one member thereof on each side of of the plane defined by said beams whereby each said pair of poles provides a field transecting said beams, and a source of pulsed current connected to energize each of said pole pairs and connected to establish a first field polarity within the two central ones of said pole pairs and to establish a reverse field polarity within the two outer ones of

said pole pairs whereby said beams are caused to converge and subsequently to diverge and return to separate parallel paths.

14. A deflector magnet structure substantially as described in claim 13 wherein said two central ones of said pole pairs are spaced apart a substantial distance whereby said two beams are made co-linear over a substantial distance and whereby the region of co-linearity of said beams is substantially free from surrounding obstructions.

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