March 26, 1968 E. B. FORSYTH 3,375,452

FERRITE ADJUSTABLE KICKER MAGNET FOR EXTRACTING BEAMS OF CHARGED PARTICLES

Filed Jan. 13, 1967 3 Sheets-Sheet 1

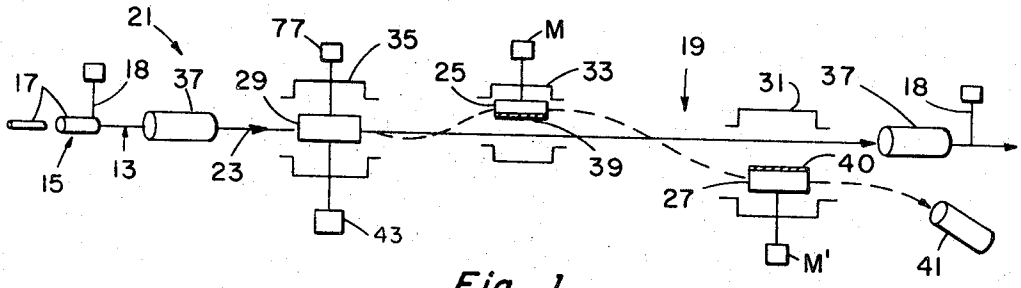


Fig. 1

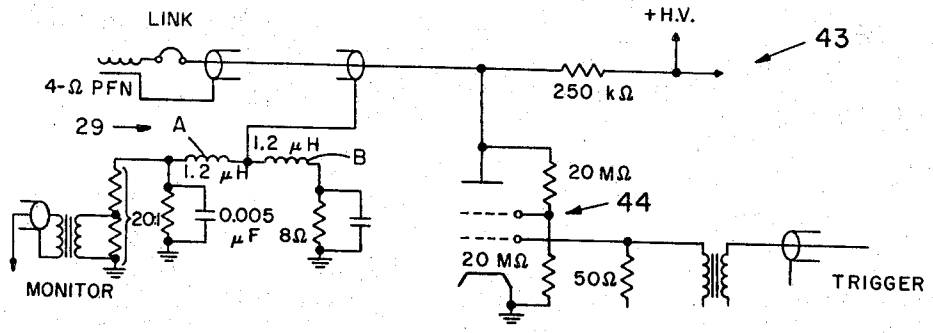


Fig. 2

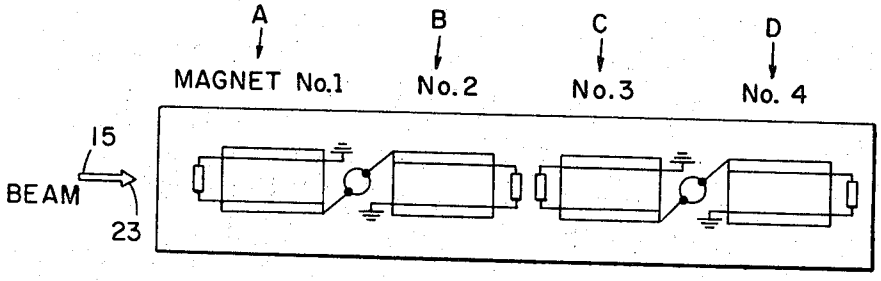


Fig. 3

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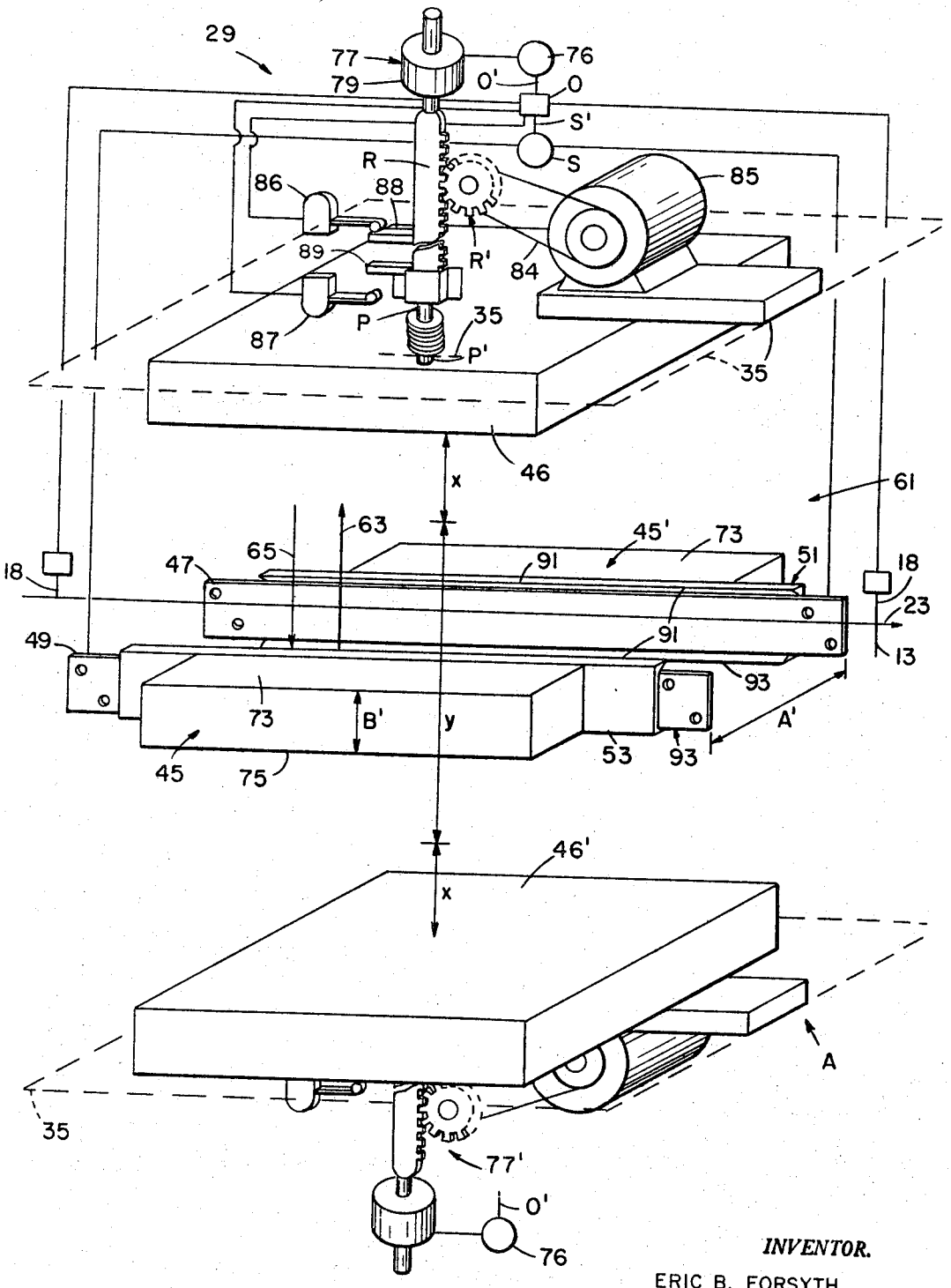


Fig. 4

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FERRITE ADJUSTABLE KICKER MAGNET FOR EXTRACTING BEAMS OF CHARGED PARTICLES

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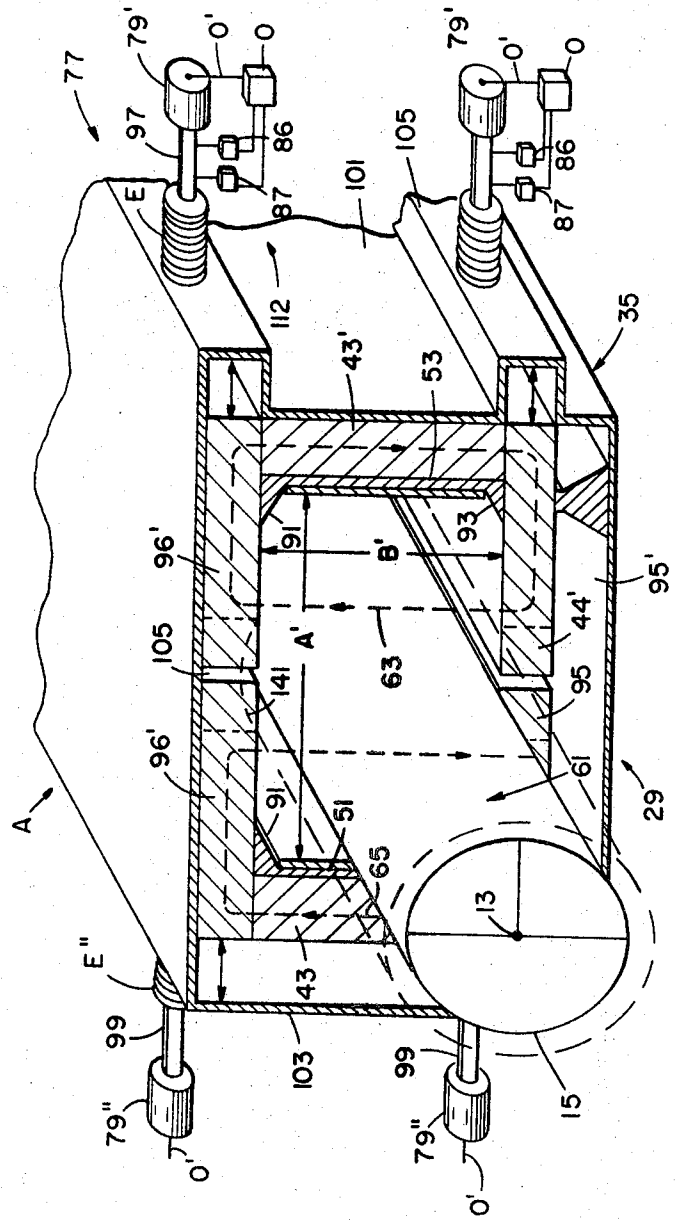


Fig. 5

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3,375,452

FERRITE ADJUSTABLE KICKER MAGNET FOR EXTRACTING BEAMS OF CHARGED PARTICLES

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7 Claims. (Cl. 328—235)

ABSTRACT OF THE DISCLOSURE

A method and apparatus for magnetically, sequentially, extracting beams of charged particles from an endless high energy accelerator ring by selectively separating non-conducting, magnetically susceptible ferrite blocks to form a large cross-section aperture for receiving large diameter low momenta beams, and selectively moving said blocks together to form a small cross-section aperture with stationary, spaced apart, ferrite blocks having stationary conductors thereon that receive small diameter, high momenta, beams and to eject these small diameter beams from the accelerator.

This invention was made in the course of, or under, a contract with the United States Atomic Energy Commission.

BACKGROUND OF THE INVENTION

1. *Field of the invention*

In high energy physics a need exists for a device capable of extracting beams of charged particles from the endless vacuum chamber of high energy accelerators. These beams vary over a wide range of betatron oscillation amplitudes and beam diameters from low beam momenta at injection to high beam momenta at ejection and are particularly of interest over an average variation of betatron oscillation amplitudes and beam diameters from about two inches to about one-half inch or less.

2. *Description of the prior art*

Stationary, constant aperture kicker magnets known heretofore do not operate efficiently at such variable beam diameters since they have been subject to severe flux degradation proportional to the square of the flux density times the aperture volume i.e. B^2V. Thus they have been subject to the disadvantage of not being able to extract all the beam particles in a small diameter beam at high beam momenta whereby these kickers have produced extremely dangerous or undesirable radiation levels due to scattering in the kicker magnets or in their associated equipment, such as the septum magnets for deflecting the beam downstream from the kicker magnet. Others, such as the movable magnets disclosed in U.S. Patent 3,128,405, which have required the manufacture and assembly of movable or flexible electrical conductors, have been subject to frequent and expensive breakdown adjustment or repair of these conductors due to wear and fatigue. Additionally, it has been advantageous to provide a practical, simple and trouble-free kicker magnet that maintains the integrity of the vacuum chamber for the charged particle beam.

It is an object of this invention, therefore, efficiently to provide a practical and economical apparatus and method for the deflection of small diameter beams of charged particles and the transmittal of large diameter beams of charged particles by providing stationary and movable, magnetically susceptible, non-conducting members that form a variable size aperture for accommodating large and small beam diameters;

It is another object to eject charged particles from a beam travelling along an endless equilibrium axis in such a way to avoid the use of movable electrical conductors;

It is another object to provide a variable aperture kicker magnet that will cause the least scattering interference with a beam of charged particles;

It is a further object to eject charged particles from a beam travelling along an endless equilibrium axis in a closed vacuum chamber in such a way as to avoid introducing vacuum leaks into the chamber;

It is a further object to minimize the stored energy in the aperture of a kicker magnet by providing a small vertical clearance when the magnet is energized and a larger vertical clearance when the magnet is not energized;

It is a still further object to reduce the weight of kicker magnets while increasing their kicking ability.

SUMMARY OF THE INVENTION

This invention provides selectively energized stationary electrical conductors, stationary magnetically susceptible members and movable magnetically susceptible members that selectively separate to form a large or open-ended aperture of predetermined dimensions for receiving a large diameter beam and selectively close to form a small cross-section rectangular shaped aperture of predetermined dimensions in timed sequence with the energization of said conductors for efficiently ejecting a small diameter beam, means for biasing the movable members to form the large or open-ended rectangular shaped aperture, a chamber means having bellows for maintaining a completely vacuum tight seal between said moveable members and said biasing means while accommodating relative movement between said chamber and said biasing means, and means for selectively limiting the movement of said moveable members to provide said predetermined dimensions in said open-ended aperture and said gap. With the proper selection and arrangement of components, as described in more detail hereinafter, the desired trouble-free ejection and vacuum integrity are achieved.

The above and further novel features and objects of the invention will appear more fully from the following detailed description when the same is read in connection with the accompanying drawings, and the novel features will be particularly pointed out hereinafter in connection with the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings where like elements are referenced alike:

FIGURE 1 is a partial schematic view of an accelerator ring incorporating the kicker system of this invention;

FIGURE 2 is a partial circuit diagram of the pulse forming network and discharge circuitry for the fast kicker of FIGURE 1;

FIGURE 3 is a partial circuit diagram of the conductors of the fast kicker of FIGURE 1;

FIGURE 4 is a partial three dimensional view of an embodiment of this invention;

FIGURE 5 is a partial three dimensional view of another embodiment of this invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

It is known that charged particle beams can be accelerated from low momenta to high momenta in the vacuum chamber of an endless accelerator ring. One such accelerator is shown and discussed in U.S. Patent 2,882,396 by E. D. Courant et al., the description and figures of which contemplate a beam travelling in an endless evacuated tube at low momenta and thereafter at higher momenta in longitudinally extending bunches close to the

speed of light. The vacuum chamber has an elliptical cross-section, and in one practical system thereof in the Brookhaven National Laboratory AGS, the tube has a vertical minor axis of about 2.7 inches and a horizontal major axis of about 6 inches to accommodate an injected beam having an average diameter of about two inches.

Focusing of the beam is based on the strong focusing or alternating gradient principle, which confines the beam along an endless equilibrium axis or orbit in the tube so that the beam does not hit the sides of the tube as the beam oscillates with a preselected small betatron oscillation amplitude along the axis. In the Brookhaven National Laboratory Alternating Gradient Synchrotron, whose principles and operation are described in the cited patent, the betatron oscillation wave length is about 300 feet and the betatron oscillation frequency is from 1–3 megacycles per second from injection to full beam energy, when the beam diameter is about .25 inch on the average. The invention hereinafter described ejects a beam of this type from an accelerator of the above-mentioned variety.

In order to explain how the method and apparatus of this invention accomplish this ejection, reference is made to FIGURE 1, wherein is illustrated an endless equilibrium orbit axis **13** along which a beam **15** of high energy particles travels in bunches **17** detected by suitable beam induction probes **18**. Orientation of the figure is shown by the arrow **19**, which is disposed radially outwardly from a point (not shown) corresponding to the center of the beam orbit in the accelerator **21**. Arrow **23**, represents the direction of the beam travel.

It is desirable to provide a fast, single-turn extracted beam of protons up to about 33 bev. energy or more with high efficiency, in beams having densities up to 10^{13} particles or more. To this end three pulsed magnets **25**, **27**, and **29** couple to the beam by coherent betatron oscillations and the magnets have their own vacuum enclosures **31**, **33** and **35** that connect with the main vacuum tube **37** of accelerator **21**. Magnets **25** and **27** have septum plates **39** and **40** dividing their magnetic fields into areas of high magnetic field and almost zero field. The fields in these magnets develop relatively slowly, being fully established immediately prior to ejection from tube **37** into tube **41**. Suitable means M and M′ withdraw both septum magnets before injection to avoid restricting the aperture size of the accelerator **21**, which as a practical matter corresponds with the size of the tube **37**, and ram the entire septum magnets inwardly toward the beam axis **13** after the beam diameter shrinks due to acceleration. The power supply (not shown) for the septum magnet **25**, comprises a closed loop, current regulating servo, whose regulating element is a bank of 200 power transistors connected in parallel. The loop compares the voltage across a shunt with a reference and amplifies the error signal. The power supply for the septum magnets is located about 80 feet from the magnet, outside the accelerator tunnel, to prevent deterioration of the power transistors due to radiation damage. The power supply for magnet **27** (the ejector magnet) is a 16,000 mf. capacitor bank with ignitron switch tubes.

Before ejection, normal acceleration occurs in the accelerator **21**, partially shown for ease of explanation, as the beam **15** lies on the zero field side of the septa **39** and **40**. The magnet **29** of this invention, receives pulses from source **43**, at a predetermined fixed time after injection of beam **15** into accelerator **21** from a suitable source (not shown) whereby this magnet's field has a rise time shorter than the time between adjacent proton bunches **17** in the accelerator **21**. Thus, the pulsed field, properly synchronized to the bunch position, deflects the beam **15** from the main vacuum tube **37** of the accelerator **21** into the high field areas of the septum magnets and out of the accelerator **21** through the transport tube **41**, which connects with the main beam tube **37**.

The power supply **43** for the fast pulsed magnet **29**, comprises low-impedance, high-voltage pulse-forming networks (PFN's) switched by thyratrons **44**, as illustrated in FIGURE 2. The pulsed field requirements of this fast kicker correspond to the current waveform associated with a line-type modulator. Thus the current must flow in the kicker in series with matched terminating resistors and the inductance of the kicker must not cause a radical change in the discharge current waveform. To this end the kicker magnet system **29** has several like sections A, B, C and D that are electrically in parallel and magnetically in series as illustrated in FIGURE 3. Each section is alike.

Referring now to FIG. 4, a practical embodiment of one section, for example section A, of the fast kicker **29** of this invention, comprises rectangular ferrite blocks **45** and **45′** and **46** and **46′**. The blocks **45** and **45′** are stationary and have dipole magnetic particle deflecting conductors **47** and **49** thereon, which are insulated from the blocks **45** and **45′** by insulators **51** and **53** and straddle the opposite sides of the axis **13** and beam **15**. Ferrite blocks **46** and **46′** straddle the top and bottom of axis **13** and have provision for a first movement that forms an open ended aperture **61** inside the blocks for a beam **15** of large cross-section. Provision is also made for a second movement to provide a small cross-section aperture **61** with a width illustrated by arrow A′ and a height illustrated by arrow B′ to accommodate the small cross-section beam **15** after acceleration in accelerator **21**. The side portion of the blocks, i.e. blocks **45** and **45′**, remain stationary, thus providing a fixed uniform dimension A′ in aperture **51**, while another portion of the blocks move relatively apart to form an increased uniform cross-section aperture **61** at least as big as the vertical distance across the injected large cross-section beam wherein the dimension Y represents the maximum height of the beam **15**. The movement provided is such as selectively to straddle the large and small cross-section beams **15** with an equal minimum small clearance from the maximum vertical beam envelope dimensions of the accelerated and injected beams **15** to the top and bottom blocks **46** and **46′** so as to prevent scattering of the particles from the beam **15**.

Energizing of the conductors **47** and **49** produces magnetic field lines, whose direction is illustrated by arrows **63** and **65**, in the small cross-section aperture **61** at right angles to the beam direction **23**, and these field lines pass through the top and bottom blocks **46** and **46′** and the side blocks **45** and **45′** in continuous paths to create a high, concentrated flux in the small cross-section aperture **61** whereby the beam deflects a sufficient amount for ejection from the accelerator **21**.

In this regard, the energization of the conductors **47** and **49** is in opposite directions in series whereby the magnetic field lines pass through the side blocks **45** and **45′** in opposite directions substantially parallel with the direction of the field lines in the aperture **61** and through the top and bottom blocks substantially at right angles to the direction of the field lines in the aperture **61**. Moreover, the directions **63** and **65** of the field lines relative to each other are opposite and rotate, with the top and bottom blocks **46** and **46′** providing the respective return paths for transmitting the magnetic field lines across the aperture **61** in continuous paths. Thus, at the intersection of a vertical plane on the axis **13** and normal to the top and bottom blocks **46** and **46′** the field lines in aperture **61** divide from each other into the top block **46** and come together in the bottom block **46′** with the field line direction **63** being counter-clockwise on one side of the plane and the field line direction **65** being clockwise on the other side of the plane.

In the embodiment, illustrated in FIGURE 4, the top and bottom blocks **46** and **46′** move relatively up and down toward and away from each other. Advantageously, when they move toward each other they form horizontal spaces adjacent the top **73** and bottom **75** of side blocks **45** and **45′** between the top and bottom blocks and their adjacent side blocks **45** and **45′** transverse to the return

paths of the magnetic field lines in the ferrite blocks as the field lines progress into and out of the top block **46** and the bottom block **46'** through the intermediary of the side blocks **45** and **45'** and the aperture **61**. These spaces which prevent shock damage to the blocks in moving together suddenly, are small relative to the height B' or width A' of the aperture **61** to minimize flux degradation in these spaces adjacent surfaces **73** and **75**. Round portions *p* and *p'* of rack R connect with block **46** through vacuum seal E, such as bellows E in the side of enclosure **35** for the blocks **45**, **45'**, **46** and **46'** and the conductors **47** and **49**, said enclosure **35** connecting in a closed system with tube **37**.

In this embodiment, source **76** energizes actuators **77** and **77'** upon command through lead O' from a control O a predetermined time after injection of beam **15** into accelerator **21** thereby to energize the actuators in the proper direction to bias the blocks **46** and **46'** selectively to increase or decrease the cross-sectional area of aperture **61** to the desired size in the proper sequence while control O connects with source S through lead S' for the energization of conductors **47** and **49** in the proper sequence.

For ease of explanation, the top actuator **77** will be described, although it is like the bottom actuator **77'** for block **46'**. This actuator, comprises linear motor **79** that is energized in one direction to move the block connected therewith inwardly and energized oppositely to move the block connected therewith outwardly. The position of the blocks is monitored by rack R, pinion R' and drive **84** that is connected between pinion R' and potentiometer **85**. Portion *p* of shaft R extends to seal E and portion *p'* of shaft R extends from the inside of seal E to the block **46** so that the block **46** is moved by shaft R.

Limit switches **86** and **87** are actuated by the movement of tabs **88** and **89** on shaft R electrically to brake the movement of motor **79** in each direction to limit the movement of shaft R at the desired predetermined positions. Thus the movement of shaft R is limited in one direction by one or the other of the limit switches.

In one sequence for an aperture **61** having a length of **60''** in kicker **29**, the field rise due to energization of conductors **47** and **49** begins just after the downstream end of one particle bunch **17** leaves the kicker **29** and the field strength rises to its maximum before the beginning of the next adjacent bunch **17** enters the aperture **61**. This requires a rise time of 200 Nano-seconds. The top actuator **77** and the like bottom actuator **77'** are simultaneously actuated from control O through lead O' selectively and sequentially to move the top and bottom blocks **46** and **46'** toward each other. Thereafter, the control O energizes conductors **47** and **49** to eject the small diameter beam.

The ferrite blocks are ground high-resistivity nickel-zinc ferrite with initial permeability of at least 500, a saturation flux density of 2900 gauss, and a maximum flux density of 1500 gauss in the ferrite. The insulators **51** and **53** which insulate the conductors **47** and **49** from the ferrite blocks **45** and **45'** comprise thin rectangular shaped channels of glass having opposite flanges **91** and **93** that prevent arc-over from the conductors to the top and botton blocks **46** and **46'**.

In another embodiment of section A of kicker **29**, illustrated in FIGURE 5, the actuator operates without gaps transverse to the magnetic field lines. To this end the ferrite block movements provide two horizontal, oppositely moving top and bottom blocks meeting across gaps coinciding with a vertical median plane through the kicker **29** on the equilibrium axis **13**. The side blocks **45** and **45'** abut with the bottom blocks **95** and **95'** and the top blocks **96** and **96'** in parallel planes. The side blocks meet the top and bottom blocks in sliding contact in parallel planes. Like actuators **77** are provided for the top and bottom blocks, but for ease of explanation the top actuators will be described.

The top actuator **77** comprises linear motors **79'** and **79''** that bias a split top block, comprising two sections or top slabs **96** and **96'**, horizontally relatively oppositely relative to bellows E. These bellows provide for the movement of the respective drive shafts **97** and **99** through the side walls **101** and **103** of vacuum enclosure **35**. These bellows are effective since they accommodate a predetermined lateral movement in opposite directions with ease, simplicity and reliability to provide a total opening of two inches across gap **105** when the blocks **96** and **96'** are biased apart. Control O energizes these motors **79'** and **79''** through lead O' selectively to move the shafts **97** and **99** inwardly and outwardly at the appropriate time, with the desired force, speed and linear movement. Suitable limit switches **86** and **87**, like those described above, limit the movement of the top and bottom blocks to predetermined dimensions by electrically braking the motors of each actuator at the proper time.

In review of the operation of the described system incorporating the fast, high rise time kicker **29** of this invention, the beam **15** initially has a large diameter at injection. An open ended aperture **61** formed by kicker **29** receives this beam with a suitable clearance *x*, e.g. .5 inch to 1 inch. After acceleration, the aperture **61** of this kicker closes to a small cross-sectional area with a like clearance tolerance. In FIGURE 5, the dotted line **141** represents the portion of the large diameter beam **15** that would hit the closed blocks **96** and **96'**. Accordingly, the blocks open sufficiently to prevent interference with this portion of the beam **15**.

After a small diameter bunch leaves the aperture **61**, the blocks move together to form a small rectangular cross-section aperture **61** with a small clearance tolerance and the conductors are energized so that they produce their peak field before the next bunch enters this small aperture **61**. Meanwhile, the septum magnets **25** and **27** are rammed inwardly whereby the field in kicker **29** deflects the beam **15** into these septum magnets and out of the accelerator **21** through tube **41**. Then the septum magnets withdraw and the kicker **29** opens up to receive the next injected large diameter beam for the beginning of the next cycle.

This invention has the advantage of providing a variable aperture fast kicker for efficiently, safely and substantially completely extracting an entire small cross-section beam from a high energy endless accelerator ring, and for receiving a large cross-section beam at injection. This kicker eliminates the heretofore known flexible or moveable electrical connections as well as the overall magnet movement required heretofore. Moreover, simple, commercially available and effective vacuum connections and accurate predetermined dimensions are provided whereby the kicker of this invention is easy to fabricate and operate, light in weight, and dependably produces higher magnetic deflecting fluxes and more complete extraction than were possible heretofore.

What is claimed is:

1. In combination with particle extracting apparatus for use with a beam of high energy charged particles traveling in a closed vacuum chamber along an endless equilibrium axis, comprising opposite electrical conducting means for producing magnetic field lines of force in said chamber, and ferrite blocks with which said conductors form an aperture for said charged particle beam and continuous paths for said field lines that concentrate said field across said axis at right angles thereto, the improvement comprising biasing means, and chamber means connected to said biasing means for maintaining the vacuum integrity of said chamber, said biasing means connecting with a portion of said blocks through said chamber means for biasing said portion of said blocks relatively to form a large cross-section aperture for receiving large diameter, low momenta beams at injection into said chamber and for moving a first portion of said blocks relatively to form a small cross-section aperture for receiving and ef-

ficiently ejecting small diameter beams at high momenta, said conductors and said remaining of said ferrite blocks being stationary, and said first portion of said ferrite blocks being moveable relative to said conductors and stationary blocks.

2. The invention of claim 1 in which said blocks form a rectangular aperture bounded by opposite vertical first blocks and opposite horizontal second blocks, said first blocks being stationary adjacent said conductors, and said second blocks being moveaable relative to each other and relative to said first blocks.

3. The invention of claim 1 in which said moveable blocks are relatively moveable vertically.

4. The invention of claim 1 in which said moveable blocks are relatively moveable, horizontally, said biasing means, comprises linear induction motors, and said chamber means having a vacuum tight bellows connected between said linear induction motors and said chamber means.

5. The invention of claim 1 having means for selectively energizing said conductors and moving said moveable ferrite blocks in a timed sequence whereby said magnetic field lines of force are bent to reach their maximum flux density in said aperture when said aperture has its smallest cross-sectional area.

6. The invention of claim 1 having means for selectively stopping said ferrite block movement to provide a small space between said moveable and fixed blocks that is smaller than the largest dimension of said aperture cross-section.

7. The invention of claim 1 having means for stopping said ferrite block movement to provide a small space between said moveable blocks in a plane that intersects said beam equilibrium axis and forms a division for receiving and transmitting adjacent magnetic field lines of force in clockwise and counterclockwise directions, said space thereby avoiding the crossing of said lines of force transverse thereto.

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