

[54] **ACHROMATIC MAGNETIC BEAM DEFLECTION SYSTEM**

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abandoned.

[52] U.S. Cl. **250/396, 250/399, 335/210**

[51] Int. Cl. **H01j 37/00**

[58] Field of Search **250/396, 398, 399;**
335/210; 328/230; 313/79, 62

[56] **References Cited**

UNITED STATES PATENTS

3,691,374 9/1972 Leboutet **250/396**

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Herbert; John J. Morrissey

[57] **ABSTRACT**

A collimated beam of non-monoenergetic charged particles, such as electrons, is passed into a magnetic beam deflection system consisting of at least three uniform field, beam bending magnets spaced apart along the central orbital axis of the beam for magnetically bending the beam by a relatively large angle as of 270°. The uniform field beam bending magnets are dimensioned, shaped, and spaced apart along the orbital axis such that the collimated beam is imaged at the beam exit plane without incurring either spatial or angular dispersion nor producing a significant increase in the spot size of the beam. Such a beam deflection system is particularly advantageous for use in an X-ray therapy machine.

27 Claims, 9 Drawing Figures

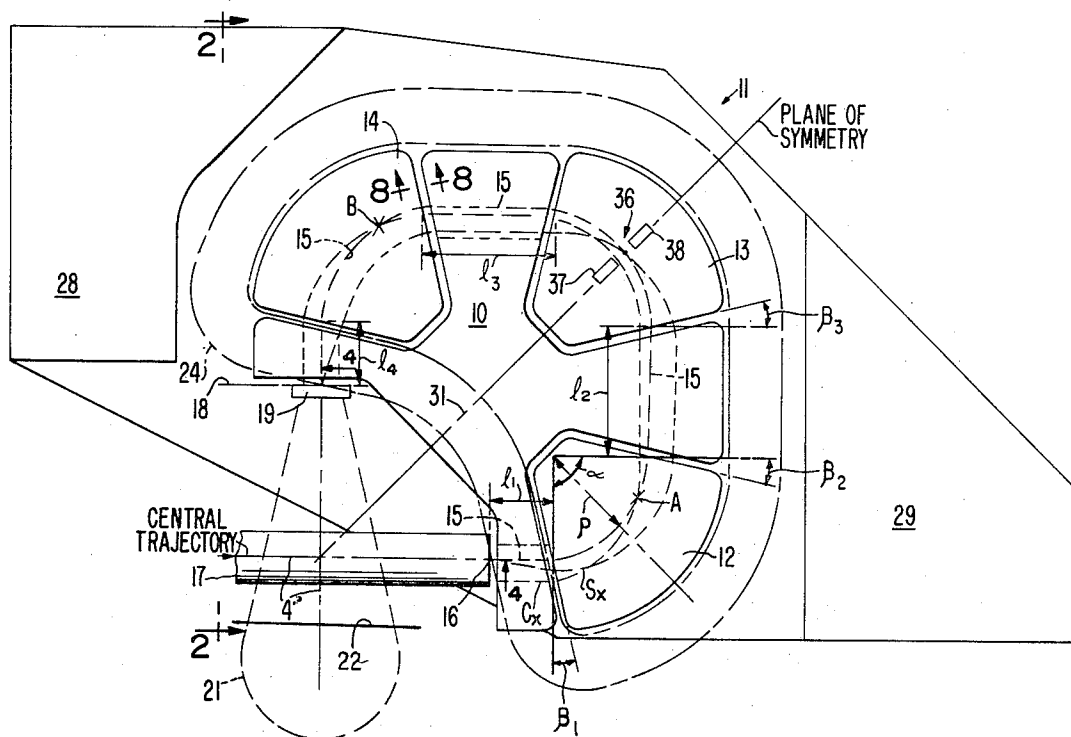


FIG. 1

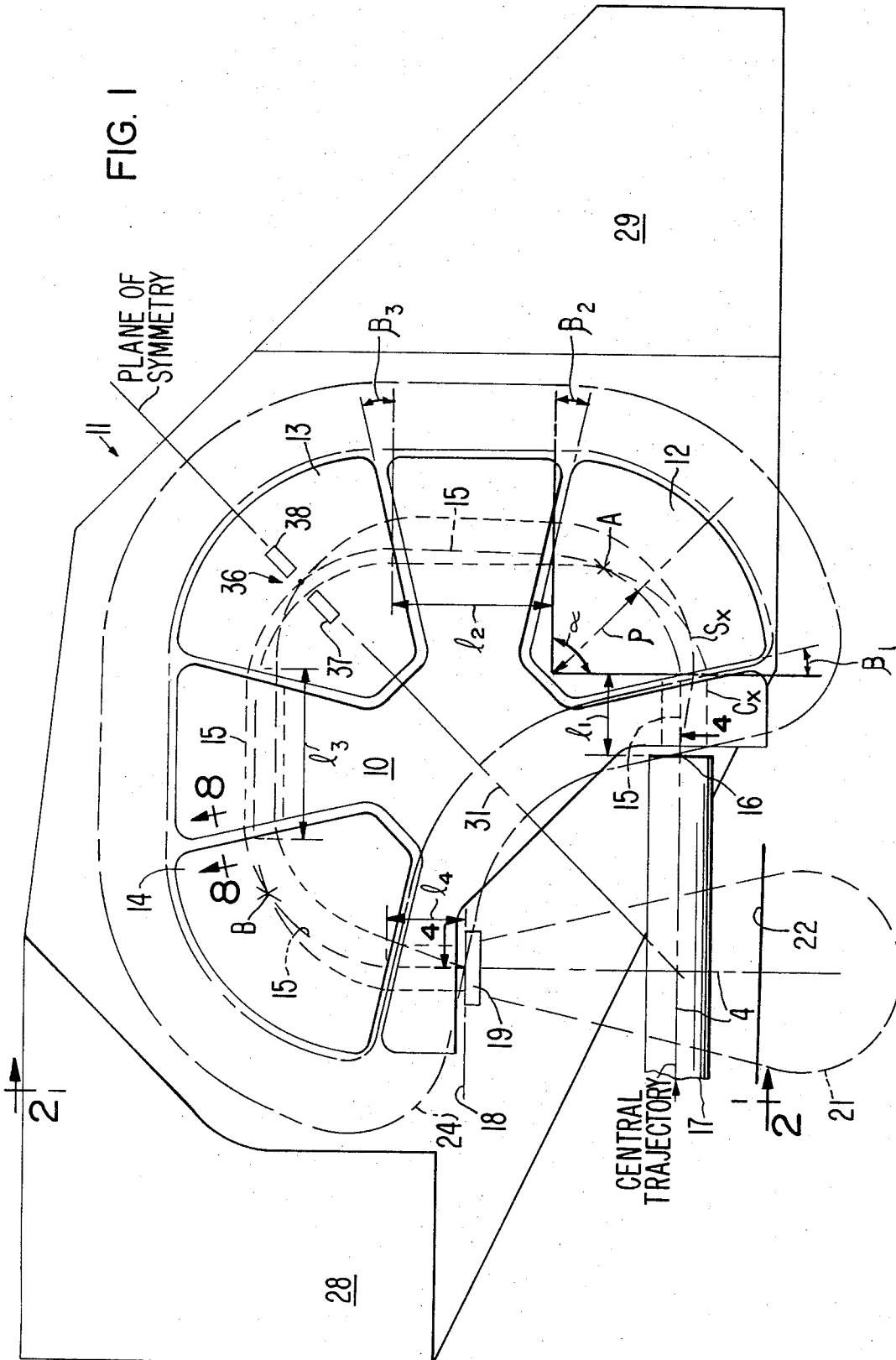


FIG. 2

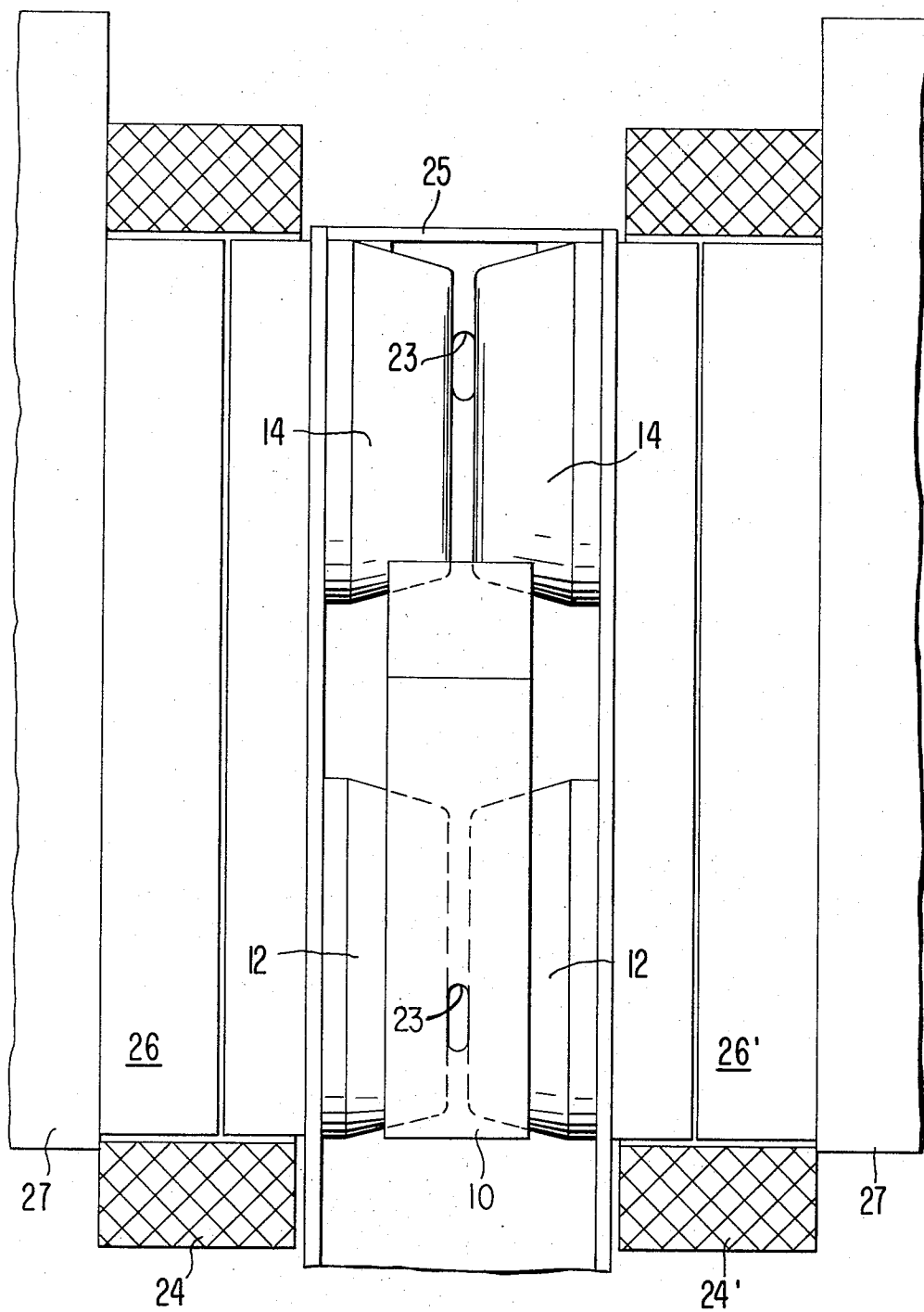


FIG. 5

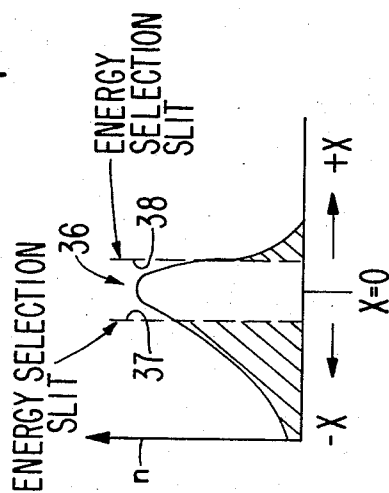
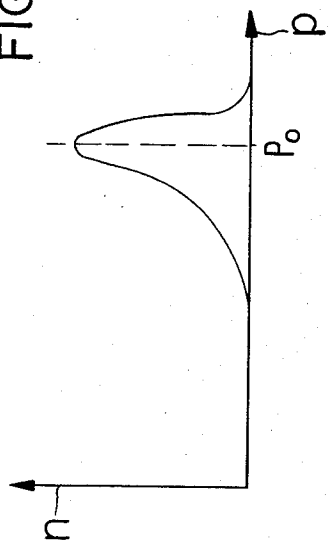


FIG. 6

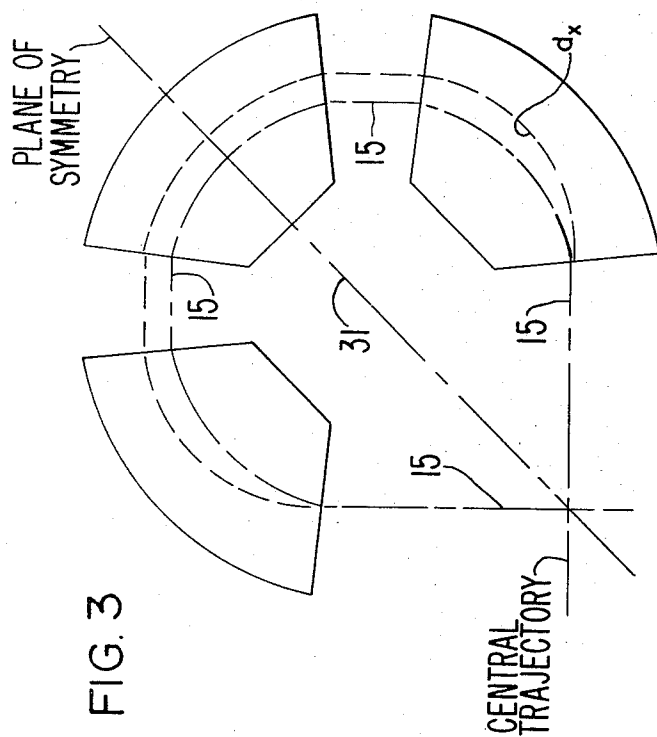


FIG. 3

FIG. 4

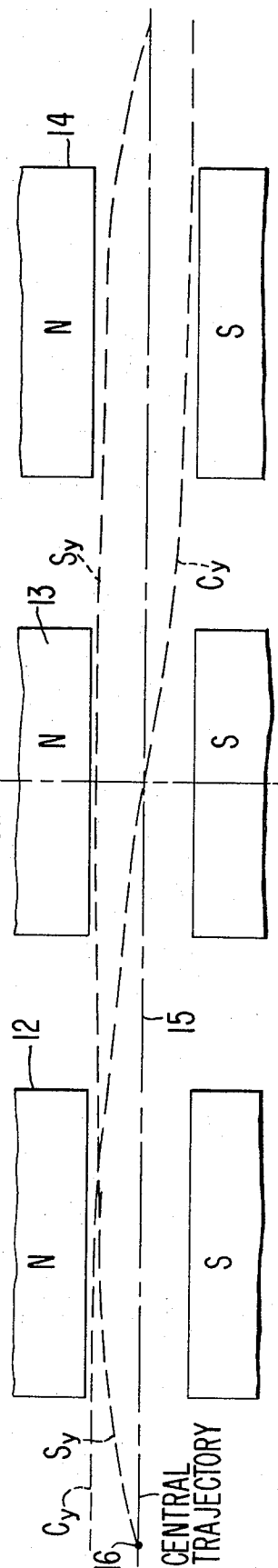


FIG. 7

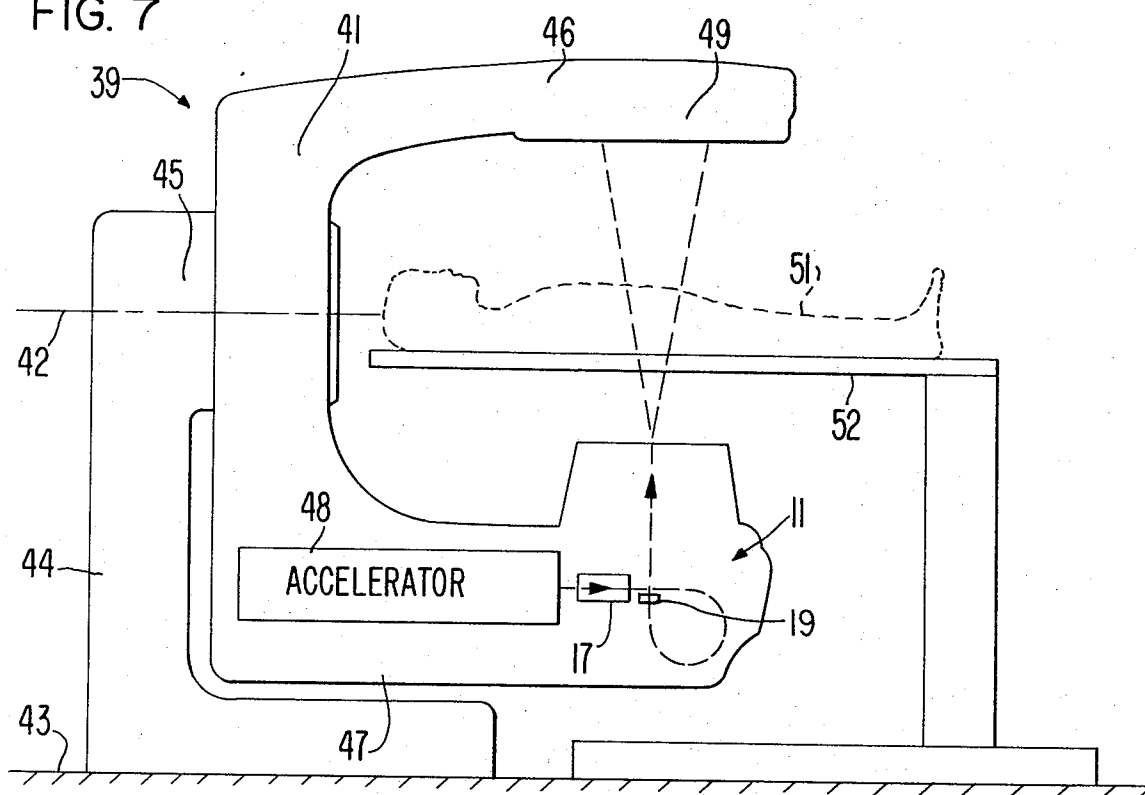


FIG. 8

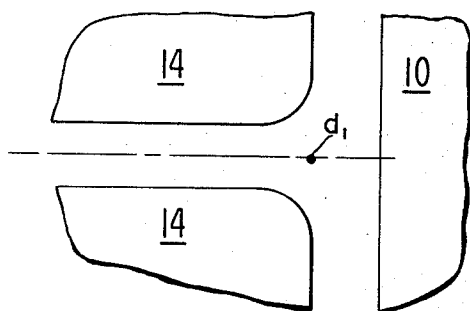
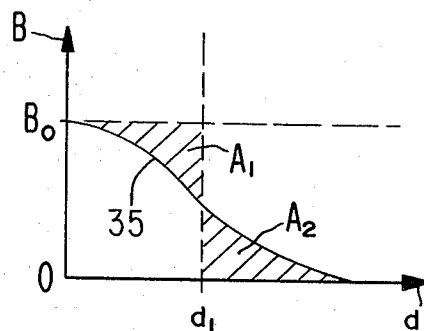


FIG. 9



ACHROMATIC MAGNETIC BEAM DEFLECTION SYSTEM

RELATED CASES

The present application is a continuation application of copending parent application U.S. Ser. No. 325,296, filed Jan. 22, 1973 now abandoned and assigned to the same assignee as the present invention.

DESCRIPTION OF THE PRIOR ART

Heretofore, achromatic beam deflection systems have been proposed for bending a non-monoenergetic beam of electrons, as collimated at the end of a linear accelerator, over a substantial angle as of 270° . The beam is bent into an X-ray target to produce a lobe of X-rays for X-ray therapy purposes. Such a beam deflection system is disclosed in U.S. Pat. No. 3,691,374 issued Sept. 12, 1972.

In this prior magnetic deflection system, the design fails to take into account spot size and angular divergence of the beam in the plane transverse to the bending plane. As a consequence, the magnetic gaps of the individual beam bending magnets must be excessively large or else beam transmission is reduced by interception of the beam on the magnet structure. In addition, beam spot diameter and angular divergence of the beam spot at the target in the transverse plane should be substantially equal to the divergence and spot diameter at the target in the bending plane or else the pattern of X-rays produced at the target is not circularly symmetric. Lack of circular symmetry in the lobe of X-rays may be corrected by asymmetric X-ray absorbing filter members but this introduces an undesired complexity into the radiation therapy machine.

Thus, it is desired to have an achromatic magnetic beam deflection system of the type wherein the deflected emergent beam particles will follow a predetermined path, with substantially no positional or angular momentum dispersion introduced by the deflection system regardless of the initial momentum of the individual beam particles. In such a system, the emergent deflected beam has essentially the same phase space configuration as the initial beam with no significant increase in spot size.

SUMMARY OF THE PRESENT INVENTION

The principal object of the present invention is the provision of an improved method and apparatus for achromatic magnetic deflection of a beam of non-monoenergetic charged particles.

In one feature of the present invention, the parameters of the magnetic beam deflection system such as β angles, i.e., angles that the beam entrance and exit faces of the individual beam bending magnets make at the points of intersection with radii of the central orbital axis, drift lengths l , bending angles α , and beam bending radii of curvature ρ of the bending magnets are all chosen such that the input beam to the deflection system is imaged at the output plane without incurring either spatial or angular dispersion or a significant increase in spot size.

In another feature of the present invention, the magnetic beam deflection system comprises three identical beam bending magnets disposed along the deflected beam path in such a manner that a plane of symmetry, substantially normal to the central orbital axis, occurs

at one-half the total beam deflection angle, whereby construction of the beam deflection system is simplified.

In another feature of the present invention, the radial focusing parameters of the magnetic deflection system are chosen to provide a waist of monoenergetic particles at a point where the non-monoenergetic particles are radially dispersed in proportion to their momentum dispersion. An energy selection slit or shaver is provided at the radial waist or relatively near thereto for momentum analyzing the beam to eliminate tails in the momentum spectrum, thereby minimizing the effect of a fluctuating momentum spectrum of the beam. In a preferred embodiment, the energy selection slit or beam shaver is located in a position such that the bulk of the radiation emanating from the momentum defining slit or shaver may be adequately shielded from the final target position and thus not interfere with the patient treatment procedure.

In another feature of the present invention, the transverse beam focusing and deflection parameters of the magnetic deflection system are chosen to provide an envelope waist midway along the central orbital axis, whereby the magnetic gap width of the bending magnets, for a given beam transmission, is minimized.

Other features and advantages of the present invention will become apparent upon a perusal of the following specification taken in conjunction with the accompanying drawings wherein:

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a plan view of a magnetic deflection system incorporating features of the present invention and depicting the beam particle trajectories in the bending plane for, the central orbital axis, initially radially divergent particles s_x , and for initially parallel radially displaced particles c_x ,

FIG. 2 is a view of the structure of FIG. 1 taken along line 2—2 in the direction of the arrows,

FIG. 3 is a simplified view similar to that of FIG. 1 depicting the central orbital axis and beam particle trajectories for momentum dispersive particles initially on the central orbital axis,

FIG. 4 is a view of the transverse plane containing the central orbital axis of the structure of FIG. 1 taken along line 4—4 in the direction of the arrows and depicting the beam particle trajectories for an initially parallel transversely displaced particle and for an initially transversely divergent beam particle,

FIG. 5 is a plot of the number of electrons versus momentum depicting the momentum distribution of a typical output beam of a linear accelerator,

FIG. 6 is a plot of the number of electrons versus radial displacement in the bending plane from the central orbital axis for the momentum analyzed beam of FIG. 1 at the plane of symmetry,

FIG. 7 is a schematic side elevational view of an X-ray therapy machine employing features of the present invention,

FIG. 8 is an enlarged sectional view of a portion of the structure of FIG. 1 taken along line 8-8 in the direction of the arrows and depicting the input face of one of the bending magnets, and

FIG. 9 is a plot of magnetic field versus distance along the orbital at the edge of a bending magnet and depicting a method for determining the effective edge of the bending magnet.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring now to FIG. 1, there is shown, in plan view, a magnetic deflection system 11 incorporating features of the present invention. The system 11 includes three uniform field bending electromagnets 12, 13 and 14 arranged along the curved trajectory defining the central orbital axis 15 of the beam deflection system 11. More particularly, the central orbital axis 15 lies in and defines the radial bending plane and is that trajectory followed by a charged particle of a reference momentum P_0 entering the deflection system 11 at the origin 16 and initially traveling in a predetermined direction which defines the initial trajectory of the central orbital axis 15. The charged particles of the beam are preferably initially collimated by a beam collimator 17 and projected through the beam entrance plane at the origin 16 into the magnetic deflection system 11.

In a typical example, the initial beam is formed by the output beam of a linear accelerator as collimated by collimator 17. As such, the entrance beam will have a certain predetermined spot size and will generally be non-monoenergetic, that is, there will be a substantial spread in the momentum of the beam particles about the reference momentum P_0 of the particle defining the central orbital axis 15. A typical momentum distribution of the particles of the beam is shown in FIG. 5.

Each of the bending magnets 12-14 bends the central orbital axis through a substantial bending angle, α , as of 90° and of bending radius ρ , each followed by or separated by rectilinear drift length portions 1₁, 1₂, 1₃ and 1₄.

A magnetic shunt structure 10, as of soft iron, is disposed in the spaces between adjacent bending magnets 12-14 and along the central orbital axis between the origin 16 and the first bending magnet 12 and between the last bending magnet 14 and the exit plane 18 at which a beam target 19 is placed for interception of the electron beam to generate an X-ray lobe 21 for treatment of the patient. The X-ray energy passes through an X-ray transparent portion of a vacuum envelope 22 defining an X-ray window of the X-ray therapy machine.

The magnetic shunt structure 10, is provided with tunnel portions 23, see FIG. 2, to accommodate passage of the beam through the shunt 10. The shunt 10 serves to provide a relatively magnetic field free region in the spaces between the beam bending magnets 12, 13 and 14, and in the spaces between the beam entrance and beam exit planes and the adjacent beam bending magnet structure.

The beam bending magnetic field regions are defined by the gaps between respective pole pieces of magnets 12-14, as shown in FIG. 2, and are energized with magnetomotive force generated by an electromagnetic coil structure split into two axially separated halves 24 and 24' and disposed outside of the vacuum envelope 25 around a split magnetically permeable coil spacer structure 26 and 26' which in turn is closed on opposite sides by magnetically permeable side return plates 27. The side return plates 27 are interconnected at opposite ends via rear and front magnetic return shunts 28 and 29, respectively, as of soft iron (see FIG. 1).

The magnetic deflection system 11 includes a plane of symmetry 31 normal to the bending plane and bisecting the total bending angle Ψ of the magnetic de-

flection system 11. Each of the bending magnets 12-14 has a respective bending angle α and a radius of curvature ρ such radius of curvature being the radius of curvature of the central orbital axis 15 within the gap of the respective bending magnet 12-14.

It has been shown that the first-order beam optical properties of any static magnetic beam deflection or transport system, possessing a magnetic median plane of symmetry such as the bending plane, is completely determined by specifying the trajectories of five characteristic particles through the system 11. This is proven in the Stanford Linear Accelerator Center (SLAC) report, No. 75 of July 1967, titled "A First- and Second-Order Matrix Theory For The Design Of Beam Transport Systems And Charged Particle Spectrometers" by Karl L. Brown, and prepared under AEC Contract AT(04-3)-515. These reference trajectories are identified by their position, slope and momentum relative to a reference central orbital axis trajectory that defines the beam optical axis of the system, namely, the central orbital axis 15.

Central orbital axis 15 lies entirely within the median or bending plane. If the momentum of the particle following the central orbital axis is P_0 , then the five characteristic trajectories are defined as follows:

s_x is the path (trajectory) followed by a particle of momentum P_0 lying in the median bending plane on the central orbital axis and diverging in the bending plane from the central orbital axis with unity slope, where "unity slope" is defined in the aforesaid SLAC report 75;

c_x is the trajectory followed by a particle of momentum P_0 lying in the median bending plane and having an initial displacement in the bending plane normal to the central orbital axis of unity with an initial slope relative to the orbital axis 15 of zero, i.e., parallel to the orbital axis;

d_x is the trajectory of a particle initially coincident with the central orbital axis but possessing a momentum of $P_0 + \Delta P$;

s_y is the trajectory followed by a particle of momentum P_0 initially on the central orbital axis and having unity slope relative thereto in the transverse plane normal to the bending plane; and

c_y is the trajectory followed by a particle of momentum P_0 having an initial displacement of unity in the transverse direction from the central orbital axis and being initially parallel to the central orbital axis.

It can be shown that, because of median plane (bending plane) symmetry of the deflection system 11, the aforesaid bending or radial plane trajectories are decoupled from the transverse or y plane trajectories, i.e., trajectories s_x , c_x and d_x are independent of trajectories s_y and c_y . The aforesaid five characteristic trajectories for the magnetic deflection system 11 are shown in FIGS. 1, 3 and 4 respectively.

Referring now to FIG. 1 and considering the initially divergent s_x trajectory, it is desired in the magnetic deflection system 11 that the output beam, i.e., the deflected emergent beam at the output plane 18 as focused onto the target 19, have the identically same properties as the collimated input beam at the beam entrance plane at the origin 16.

It has been proven in SLAC report 91, titled "TRANSPORT/360 A Computer Program For Designing Charged Particle Beam Transport Systems" prepared

for the U.S. Atomic Energy Commission under Contract No. AT(04-3)-515, dated July 1970, at page A-45 that for any place in the deflection system 11 where the two different types of trajectories, namely, the cos like trajectories (c_x, c_y) and sin like trajectories (s_x, s_y) are paired for a given plane and related such that one type of trajectory is experiencing a crossover of the orbital axis where the other type of trajectory is parallel to the orbital axis, there will be a waist in the beam for that particular plane, namely bending plane (x-plane for the paired s_x and c_x terms) or transverse plane (y-plane for the paired s_y and c_y term).

In the magnetic deflection system 11, it is desired to have a beam waist in the bending plane of the beam at the mid-plane of symmetry 31. Accordingly the sin trajectory s_x is deflected to a crossover of the orbital axis 15 at the mid-plane of symmetry 31, whereas the cos trajectory c_x is focused through a crossover at A and back into parallelism with the orbital axis 15 at the mid-plane of symmetry 31. This allows a radial waist (waist in the bending plane) at the mid-plane of symmetry 31.

The momentum dispersive trajectory d_x (See FIG. 3) is focused to parallelism with the orbital axis 15 at the mid-plane of symmetry 31. This assures maximum momentum analysis since at the mid-plane of symmetry 31 the momentum dispersive particles, i.e., particles with ΔP from P_0 , will have maximum radial displacement from the central orbital axis 15 and such displacement will be proportional to ΔP for the particular particle. This combined with the radial waist for the non-momentum dispersive s_x and c_x particles allows the placement of a momentum defining slot 36 at the mid-plane of symmetry to achieve momentum analysis of the beam for shaving off the tails of the momentum distribution of the beam as more fully described below with regard to FIGS. 5 and 6. This also places the momentum analyzer 36 at a region remote from the target 19 such that X-rays emanating from the analyzer are easily shielded from the X-ray treatment zone.

Referring now to FIG. 4 there is shown the desired trajectories s_y and c_y in the transverse plane (y-plane) which is transverse to the bending plane. As above stated, a waist in the transverse plane occurs where one of the trajectories s_y and c_y is parallel to the orbital axis while the other is crossing over the orbital axis 15. A minimum magnetic gap width for the beam deflection magnets 12, 13 and 14 will be achieved if a beam waist in the transverse plane occurs at the midplane of symmetry 31. Accordingly the sin term (s_y) is focused to parallelism with the orbital axis at the midplane 31 while the cos term (c_y) is focused to a crossover of the orbital axis 15 at the midplane of symmetry 31.

The various parameters of the beam bending magnet system 11 are chosen to achieve the aforedescribed trajectories s_x, c_x, d_x, s_y and c_y as illustrated in FIGS. 1, 3 and 4. More particularly, the conditions and parameters for the magnet system 11 that must be fulfilled can be established by reference solely to certain first-order monoenergetic trajectories traversing the system 11.

First order beam optics may be expressed by the matrix equation:

$$\vec{X}(1) = \vec{R}\vec{X}(0)$$

Eq. (1)

relating the positions and angles of an arbitrary trajectory relative to a reference trajectory at any point in

question, such as an arbitrary point designated position (1), as a function of the initial positions and angles of the trajectory at the origin (0) of the system, i.e., at origin 16 herein designated (0). The proposition of Equation (1) is known from the prior art, such as the aforesaid SLAC Report No. 75 or from an article by S. Penner titled "Calculations of Properties of Magnetic Deflection Systems" appearing in the Review of Scientific Instruments, Volume 32, No. 2 of February 1961, see pages 150-160.

Thus, at any specified position in the system 11, an arbitrary charged particle is represented by a vector, i.e., a single column matrix, $\vec{X}$ whose components are the positions, angles, and momentum of the particle with respect to a specified reference trajectory, for example the central orbital axis 15. Thus,

$$\vec{X} = \begin{bmatrix} x \\ \theta \\ y \\ \Phi \\ l \\ \delta \end{bmatrix}$$

Eq. (2)

where:

x = the radial displacement of the arbitrary trajectory with respect to the assumed central orbital trajectory 15;

θ = the angle this arbitrary trajectory makes in the bending plane with respect to the assumed central orbital trajectory 15;

y = the transverse displacement of the arbitrary trajectory in a direction normal to the bending plane with respect to the assumed central orbital trajectory 15;

Φ = the angular divergence of the arbitrary trajectory in the transverse plane with respect to the assumed central trajectory 15;

l = the path length difference between the arbitrary trajectory and the central orbital trajectory 15; and
 $\delta = \Delta P/P_0$ and is the fractional momentum deviation of the particle of the arbitrary trajectory from the assumed central orbital trajectory 15.

In Equation (1), R is the matrix for the beam deflection system between the initial (0) and final position (1), i.e., between positions of the origin (0) and the point in question, position (1). More particularly, the basic matrices for the various beam deflecting components such as drift distance l , angle of rotation β of the input or output faces of the individual bending magnets 12-14, and the bending angle α are as follows:

$$R_1 = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Eq. (3)

$$R_\beta = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ \frac{\tan \beta}{\rho} & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & \tan(\beta - \psi) & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

ψ = Correction term resulting from finite extent of fringing fields. Note: It is not the total angle of bend as used elsewhere herein.

Eq. (4)

$$R\alpha = \begin{bmatrix} \cos \alpha & \rho \sin \alpha & 0 & 0 & 0 & \rho(1-\cos \alpha) \\ -\sin \alpha & \cos \alpha & 0 & 0 & 0 & \sin \alpha \\ \rho & 0 & 1 & \rho\alpha & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ \sin \alpha & \rho(1-\cos \alpha) & 0 & 0 & 1 & \rho(\alpha \sin \alpha) \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad \text{Eq. (5)}$$

Thus, the matrix R for the first bending magnet is given by $R_{BEND} = (R\beta_2)(R\alpha_1)(R\beta_1)$ where β_1 is the angle of rotation of the plane of the input face relative to the radius of the central orbital axis at their point of intersection, and β_2 is the similarly defined angle of rotation of the output face of the first bending magnet relative to the central orbital axis 15, as shown in FIG. 1 and as defined by the abovesited Penner article at FIG. 2 of page 153 and the abovesited SLAC report 91 at FIG. 748A15 of page 2-4. Likewise the matrix of the first half of the second bending magnet is given by

$$R_{1/2 BEND} = R\alpha_2 R\beta_3. \quad \text{Eq. (6)}$$

where $R\alpha_2$ is identical to $R\alpha$ of Eq. (5) except that the values for α in Eq. (6B) are one half the values of α in Eq. (5).

Thus the matrix for the total system 11 to the symmetry plane 31 in the bending plane is $R_{SUM} = (R_{1/2 BEND})(R_{12})(R_{BEND})(R_{11})$.

The matrix R to the mid-plane of symmetry 31 is as follows:

$$R_{SYM} = \begin{bmatrix} R(11) & R(12) & 0 & 0 & 0 & R(16) \\ R(21) & R(22) & 0 & 0 & 0 & R(26) \\ 0 & 0 & R(33) & R(34) & 0 & 0 \\ 0 & 0 & R(43) & R(44) & 0 & 0 \\ R(51) & R(52) & 0 & 0 & 1 & R(56) \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad \text{Eq. (7)}$$

where the elements of the matrix comprise $R(ij)$ where i refers to the row and j to the column position in the matrix. Because of the symmetry on opposite sides of the bending plane, the matrix R is decoupled in the x (bending plane) and y (transverse) planes.

The matrix elements are related to the aforescribed trajectories as follows:

$$R(12) = s_x; R(11) = c_x; R(16) = d_x; R(34) = s_y; \text{ and } R(33) = c_y.$$

Referring now to the matrix R_{SUM} , Eq. (7) above, and to the aforescribed preferred trajectories, at the mid-point of the system, namely, at the symmetry plane 31 where intercepted by the central orbital axis 15, $R(16)$ (the spatial dispersion) d_x is a maximum in this design. At this same point $R(12) = R(21) = 0$, namely s_x is a crossover and the first derivative of c_x is zero, namely, parallel to the orbital axis 15. This corresponds to a waist of the source, i.e., the collimator, thus permitting momentum analysis of the beam at the mid-plane 31.

The preferred magnetic deflection system 11 is further characterized by trajectory $R(33) = R(44) = 0$ at the mid-plane of symmetry 31. Thus at the mid-point c_y is focused to a crossover of the orbital axis 15 while the first derivative of s_y is zero, i.e., $s_y' = R(44) = 0$, i.e.,

s_y is parallel to the orbital axis at the mid-plane of symmetry 31. This assures a mid-plane waist in the transverse beam envelope, such waist being independent of the initial phase space area of the beam. Since the magnetic elements are symmetrical about the mid-plane of symmetry 31 so is the beam envelope. When this condition obtains at the mid-plane of the system, not only is maximum transmission of the electron beam through the magnetic deflection system assured, to the symmetry of the system assures that both $R(34)$ and $R(43)$ terms are identically zero at the target location 19. This is equivalent to stating that both the sine-like term and the derivative of the cosine-like term are zero. These conditions are precisely the conditions required for co-incidence of point-to-point focusing and for a waist, as has been shown in the SLAC Report No. 91 aforesited.

At the end of the system, i.e., at the target 19, $R(12) = R(34) = 0$ meaning that point-to-point imaging occurs in both the radial and the transverse planes that the final beam spot size is stable relative to the input defining collimator 17. Furthermore, $|R(11)| = |R(33)| = 1$ assuring unity magnification of the initial beam spot size.

Considering angular dispersion of the beam, by requiring the derivative of the dispersion $R(26)$ term to go to zero at the mid-plane 31 of the system 11, both the dispersion term $R(16)$ and its derivative $R(26)$ are zero at the output. This is the necessary and sufficient condition that the system be achromatic.

Thus, from the above discussion it has been shown that in the preferred magnetic deflection system 11, the following matrix elements should all have zero value at the mid-plane of symmetry 31. In other words, $R(12) = R(21) = R(26) = R(33) = R(44) = 0$. This statement comprises five simultaneous matrix equations and at least five unknowns, namely, α , l_1 , β_1 , β_2 , l_2 and β_3 . In the preferred magnetic deflection system 11 of the present invention, β_1 is equal to β_2 which is equal to β_3 and α_1 equals α_2 equals α_3 .

The aforesited five simultaneous matrix equations can be solved by hand. However, this is a very tedious process and a more acceptable alternative is to solve the five simultaneous equations by means of a general purpose computer programmed for that purpose. A suitable program is one designated by the name TRANSPORT. A copy of the program, run onto one's own magnetic tape is available upon request and the appropriate backup documentation is available to the public by sending requests to the Program Librarian, Linda Lorenzetti, at SLAC, P.O. Box 4349, Stanford, Calif. 94305. The aforesited SLAC Report No. 91 is a manual describing how to prepare data for the TRANSPORT computation, and this manual is available to the public from the Reports Distribution Office at SLAC, P.O. Box 4349, Stanford, Calif. 94305.

In designing the magnetic deflection system 11 of the present invention, the fringing effects of the various bending magnets should be taken into account. More particularly, the effective input and output faces of the bending magnet do not occur at the boundary of the region of uniform field but extend outwardly of the uniform field region by a finite amount. The effective boundary is depicted as d_1 in FIGS. 8 and 9 and is that point where the cross hatched area A_1 of FIG. 9 is equal

to the cross hatched area A_2 . Area A_1 is that region of the plot between the actual magnetic field strength line 35 and that value of uniform magnetic field strength B_0 in the gap of the bending magnet 14 and area A_2 is that cross hatched area lying under the magnetic field intensity curve 35 between the effective boundary d_1 and the point at which the magnetic fringing field goes to zero amplitude. The K_1 coefficient in the pole face rotation matrix, shown at page 2-3 of the SLAC Report No. 91, takes into account the effective boundary of the bending magnet to compensate for the fringing field. In a clamped magnet of the type shown in FIGS. 1-4, the typical value for K_1 is approximately 0.4 as indicated at page 16-5 of the aforementioned SLAC Report No. 91.

Referring now to FIGS. 5 and 6 there is shown the momentum distribution of the typical output beam of the collimated linear electron accelerator. As previously pointed out above, the magnetic deflection system 11 of FIGS. 1-4 serves to provide a momentum analysis of the beam at the plane of symmetry 31. Accordingly, an energy selection slit 36 is preferably provided at the plane of symmetry for shaving from the momentum distribution of FIG. 5 the tails thereof, whereby the momentum distribution of the final beam as focused onto the target 19 is more nearly monoenergetic as contrasted with the beam at the output of the collimator 17. As shown in FIG. 6, the momentum analysis slit 36 comprises a pair of beam shaving vanes 37 and 38 radially displaced from the central orbital axis 15 by predetermined amounts for shaving the respective high and high momentum tails from the momentum analyzed beam. As can be seen by reference to FIGS. 5 and 6, most of the momentum tail occurs at the low momentum side of the distribution and, thus if desired, only one of the momentum selection vane members 37 may be employed as desired for stopping the low momentum particles. The X-rays emanating from the momentum selection slit 36 are easily shielded from the patient and target 19, as the lobe of X-rays generated by such interception of the beam tends to be directed in a substantially different direction than that of the desired X-ray lobe 21.

Referring now to FIG. 7 there is shown the magnetic deflection system 11 as typically employed in an X-ray therapy machine 39. More particularly, the therapy machine 39 comprises a generally C-shaped rotatable gantry 41 rotatable about an axis of revolution 42 in the horizontal direction. The gantry 41 is supported from the floor 43 via a pedestal 44 having a trunnion 45 for rotatably supporting the gantry 41. The gantry 41 includes a pair of generally horizontally directed parallel arms 46 and 47. A linear electron accelerator 48 is housed within arm 47 and a magnetic deflection system 11 and target 19 are disposed at the outer end of the horizontal arm 47 for projecting a beam of X-rays between the outer end of the arm 47 and an X-ray absorbing element 49 carried at the outer end of the other horizontal arm 46. The patient 51 is supported from couch 52 in the lobe of X-rays for therapeutic treatment.

Advantages of the magnetic deflection system 11 of the present invention include achromatic beam deflection through a substantial angle such that the collimated electron beam is imaged at the target 19 without incurring either spacial or angular dispersion nor a significant increase in spot size. In addition, the beam deflection system 11 is compact and greatly simplified by

employing three identical beam bending magnets. The gap requirements of the beam bending magnet system are reduced by the provision of a parallel-to-point focus in the transverse plane at the plane of symmetry 31.

Although, as thus far described, the total bending angle Ψ of the beam deflection system 11, as previously illustrated, is 270° this is not a requirement of the present invention. Other bending angles are also possible employing the techniques of the present invention. Having all of the beam bending magnets 12-14 bending the beam in the same sense is an important feature of this invention, but the use of three magnets is not an essential feature. For example, the second magnet 13 may be split into two magnets with a drift space in between and with the plane of symmetry passing through the added drift space. This alternative construction would facilitate placement of the momentum selection slit 36.

In a typical magnetic deflection system 11 for bending a beam of electrons from the collimated output of a linear accelerator onto a target 19, the magnetic field strength and accelerator output beam central momentum P_0 are chosen such that the central orbital axis 15 has a radius of curvature ρ of 1.97" and the magnetic deflection system parameters meeting the aforementioned reference trajectories s_x, c_x, s_y, c_y, d_x have the following values: $l_1 = l_4 = 1.53$ inches, $\beta_{1-6} = 13.2^\circ$, $l_2 = l_3 = 3.06$ inches, $K = 0.4$, $\alpha_{1-3} = 90^\circ$, magnet gap width = 0.22 inch.

Although the preferred position for the momentum analysis slit 36 is at the mid-plane of symmetry 31, the slit 36 can also be placed in between adjacent beam bending magnets, i.e., between magnets 12 and 13 or between magnets 13 and 14. The resolving power of the slit 36 is reduced somewhat in this position but physical realization of the slit 36 is facilitated.

What is claimed is:

1. In a method for achromatic magnetic deflection of a beam of non-monoenergetic charged particles through a bending angle Ψ along a central orbital axis defined by the trajectory of a charge particle of a reference momentum P_0 is a bending plane between transverse beam entrance and beam exit planes the steps of:
 - 45 subjecting the beam of charged particles to a series of magnetic deflection forces for;
 - 46 focusing beam particles of the reference momentum P_0 which are initially radially displaced in the bending plane from the orbital axis at the beam entrance plane to first and second crossovers of the central orbital axis and also to trajectories with approximately zero slope relative to the orbital axis at a region along the orbital axis intermediate the beam entrance and beam exit planes;
 - 50 focusing beam particles of the reference momentum P_0 having trajectories which are on and angularly divergent from the orbital axis in the beam bending plane at the beam entrance plane to a crossover of the orbital axis at a region along the orbital axis intermediate the beam entrance and beam exit planes;
 - 55 focusing beam particles of the reference momentum P_0 which are initially displaced from and parallel to the orbital axis in the transverse plane at the beam entrance plane to a crossover of the central orbital axis at a region along the orbital axis intermediate the beam entrance and beam exit planes;
 - 60 focusing beam particles of the reference momentum P_0 which are initially displaced from and parallel to the orbital axis in the transverse plane at the beam entrance plane to a crossover of the central orbital axis at a region along the orbital axis intermediate the beam entrance and beam exit planes;
 - 65 focusing beam particles of the reference momentum P_0 which are initially displaced from and parallel to the orbital axis in the transverse plane at the beam entrance plane to a crossover of the central orbital axis at a region along the orbital axis intermediate the beam entrance and beam exit planes;

focusing beam particles of the reference momentum P_0 which have initial trajectories on and angularly divergent from the orbital axis in the transverse plane at the beam entrance plane to a crossover of the orbital axis at the beam exit plane and to trajectories having zero slope relative to the orbital axis at a region along the orbital axis intermediate the beam entrance and beam exit planes; and

achromatically focusing beam particles of a momentum differing from the reference momentum P_0 and having a trajectory initially coincident with the orbital axis at the beam entrance plane to the orbital axis at the beam exit plane.

2. The method of claim 1 wherein said beam particles initially radially displaced in the bending plane from and parallel to the orbital axis at the beam entrance plane are focused to trajectories which have approximately zero slope relative to the orbital axis at a region which is approximately midway along the orbital axis between the beam entrance plane and the beam exit plane, such mid region being in a transverse plane of symmetry occurring at a beam bending angle of $\Psi/2$.

3. The method of claim 2 wherein said beam particles which are focused to first and second crossovers of the orbital axis have such crossovers on opposite sides of said mid-plane of symmetry.

4. The method of claim 1 wherein said beam particles initially angularly divergent in the bending plane from and on the orbital axis at the beam entrance plane are focused to the crossover of the orbital axis at a mid transverse plane of symmetry occurring at a beam bending angle of $\Psi/2$.

5. The method of claim 1 wherein said beam particles initially transversely displaced from the orbital axis in the transverse plane at the beam entrance plane are focused to the crossover of the orbital axis at a transverse mid-plane of symmetry occurring at beam bending angle of approximately $\Psi/2$.

6. The method of claim 1 wherein said beam particles initially angularly divergent from and on the orbital axis in the transverse plane at the beam entrance plane are focused to trajectories having zero slope relative to the orbital axis substantially at a transverse mid plane of symmetry at a beam bending angle of approximately $\Psi/2$.

7. The method of claim 1 wherein said beam particles initially transversely displaced from the orbital axis in the transverse plane at the beam entrance plane are focused to the crossover of the orbital axis at a transverse mid-plane of symmetry occurring at a beam bending angle of approximately $\Psi/2$, and wherein the beam particles initially angularly divergent from and on the orbital axis in the transverse plane at the beam entrance plane are focused to trajectories having zero slope relative to the orbital axis substantially at a transverse plane of symmetry at a beam bending angle of approximately $\Psi/2$.

8. The method of claim 1 including the step of, shaving off a radial edge of the beam at said plane of symmetry occurring at a beam bending angle of $\Psi/2$.

9. The method of claim 1 wherein the series of magnetic beam deflecting forces are produced by applying the magnetic field of at least three pairs of magnetic poles spaced apart along the central orbital axis to direct their respective magnetic fields across said central orbital axis in the transverse direction, such magnetic poles being of a polarity such that all of the applied

magnetic fields of the three pairs of magnetic poles are parallel and in the same sense.

10. The method of claim 9 wherein at least two of the three sets of magnetic pole pairs are substantially identical and each identical pole pair is energized to produce substantially equal transverse magnetic fields on the central orbital axis.

11. The method of claim 1 wherein said bending angle Ψ is approximately 270° .

12. In an apparatus for achromatic magnetic deflection of a beam of non-monoenergetic charged particles through a bending angle Ψ along a central orbital axis defined by the trajectory of a charged particle of a reference momentum P_0 in a bending plane between transverse beam entrance and beam exit planes:

means for magnetically deflecting beam particles of the reference momentum P_0 which are initially radially displaced in the bending plane from the orbital axis and initially parallel to the orbital axis at the beam entrance plane into a trajectory having first and second crossovers of the orbital axis, and such trajectory having approximate zero slope relative to the orbital axis at a region along the orbital axis intermediate the beam entrance and beam exit planes;

means for magnetically deflecting beam particles of the reference momentum P_0 and which are initially on and angularly divergent from the orbital axis in the beam bending plane at the beam entrance plane into trajectories having a crossover of the orbital axis at a region along the orbital axis intermediate the beam entrance and beam exit planes;

means for magnetically deflecting beam particles of the reference momentum P_0 and which are initially displaced from and parallel to the orbital axis in the transverse plane at the beam entrance plane into trajectories having a crossover with the central orbital axis at a region along the orbital axis intermediate the beam entrance and the beam exit planes;

means for magnetically deflecting beam particles of the reference momentum P_0 and having initial trajectories on and angularly divergent from the orbital axis in the transverse plane at the beam entrance plane into trajectories having a crossover of the central orbital axis at the beam exit plane and such trajectories having zero slope relative to the orbital axis at a region along the orbital axis intermediate the beam entrance and beam exit planes; and

means for magnetically deflecting beam particles of a momentum differing from the reference momentum P_0 and having trajectories initially coincident with the orbital axis at the beam entrance plane into trajectories that are achromatically focused to the orbital axis at the beam exit plane.

13. The apparatus of claim 12 wherein said means for magnetically deflecting said beam particles initially radially displaced in the beam bending plane and parallel to the orbital axis to trajectories having approximately zero slope includes, means for focusing said particles to trajectories which have approximately zero slope relative to the orbital axis at a transverse mid-plane of symmetry occurring at a bending angle of $\Psi/2$.

14. The apparatus of claim 13 wherein said means for deflecting said beam particles to first and second crossovers of the orbital axis includes, means for focusing said particles to trajectories having crossovers of the

orbital axis on opposite sides of said mid-plane of symmetry.

15. The apparatus of claim 12 wherein said means for magnetically deflecting said particles which are initially angularly divergent in the bending plane from and on the orbital axis at the beam entrance plane includes, means for focusing said particles to the crossover of the orbital axis at a mid-transverse plane of symmetry occurring at a bending angle of $\Psi/2$.

16. The apparatus of claim 12 wherein said means for magnetically deflecting said beam particles which are initially transversely displaced from the orbital axis in the transverse plane at the beam entrance plane includes, means for deflecting said particles to the crossover of the orbital axis at a transverse mid-plane of symmetry occurring at a beam bending angle of approximately $\Psi/2$.

17. The apparatus of claim 16 wherein said means for deflecting said beam particles initially angularly divergent from and on the orbital axis of the transverse plane at the beam entrance plane includes, means for focusing said trajectories to substantially zero slope relative to the orbital axis substantially at a transverse mid-plane of symmetry at a beam bending angle of approximately $\Psi/2$.

18. The apparatus of claim 12 wherein said means for magnetically deflecting said beam particles initially angularly divergent from and on the orbital axis in the transverse plane at the beam entrance plane includes, means for focusing said particles to trajectories having zero slope relative to the orbital axis at a point substantially at a transverse mid-plane of symmetry at a beam bending angle of approximately $\Psi/2$.

19. The apparatus of claim 12 including, means for shaving off a radial edge of the beam at a region which is approximately mid-way along the orbital axis between the beam entrance plane and the beam exit plane.

20. The apparatus of claim 12 wherein said means for producing a series of magnetic beam deflection forces comprises, at least three pairs of magnetic poles positioned along the central orbital axis to direct their re-

spective magnetic fields across said central orbital axis in the transverse direction and in the same direction.

21. The apparatus of claim 20 wherein at least two of said three sets of magnetic pole pairs are substantially identical, and means for energizing each identical pole pair to produce substantially equal transverse magnetic fields on the central orbital axis.

22. The apparatus of claim 21 wherein each pair of said magnetic pole means has an input face and an output face each defining an edge extending across the orbital axis, and wherein each of said input and output edges is inclined at substantially the same angle β to the central orbital axis.

23. The apparatus of claim 12 wherein said beam bending angle Ψ is approximately 270° .

24. The apparatus of claim 12 including, shunt means defining a magnetically permeable body disposed in between adjacent angularly spaced sets of said pole pairs for shielding the beam from magnetic fields fringing between adjacent pole pairs, said magnetically permeable body having a passageway therein for passage of the beam therethrough.

25. The apparatus of claim 12 including, linear accelerator means for generating a beam of electrons and for feeding the beam of electrons to the beam deflection apparatus, X-ray target means disposed to receive the deflected beam of electrons for generating a lobe of X-rays, and means for directing said lobe of X-rays onto an object to be irradiated.

26. The apparatus of claim 25 including, collimator means disposed between said linear accelerator means and said beam deflection apparatus for collimating the electron beam prior to magnetic deflection thereof.

27. The apparatus of claim 12 including, wherein said magnetic deflection means includes a plurality of beam bending magnets disposed along the central orbital axis and including means for shaving off a radial edge of the beam in the beam bending plane at a region along the central orbital axis in between adjacent ones of said beam bending magnets.

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