July 26, 1966 **H. S. GORDON** **3,263,136**

HIGH ENERGY ACCELERATOR MAGNET STRUCTURE

Filed Jan. 20, 1964

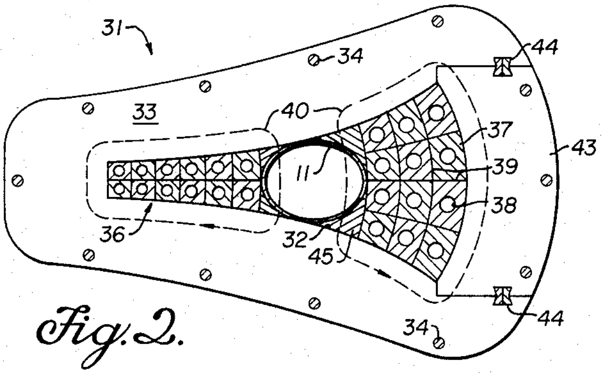

Fig. 2.

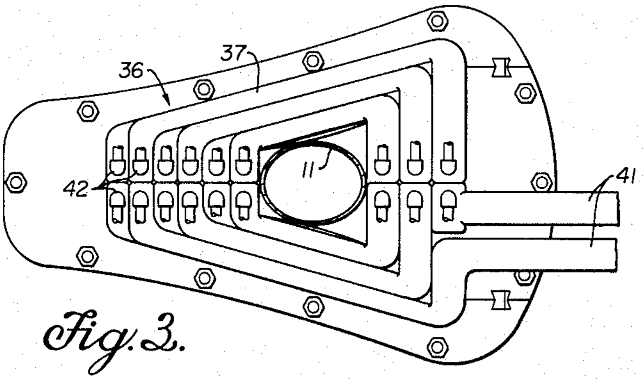

Fig. 3.

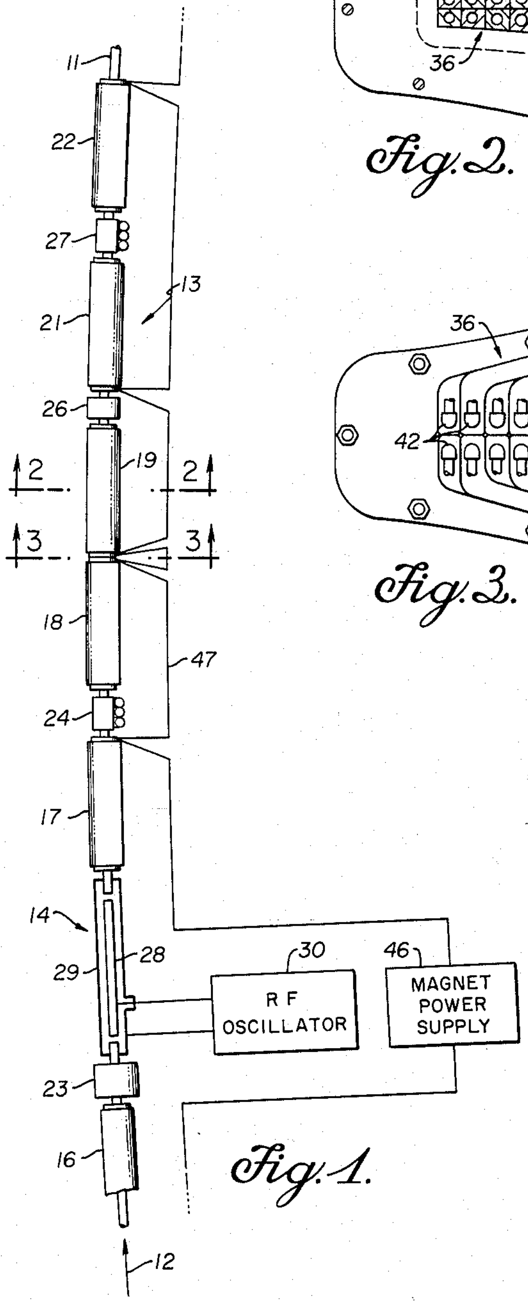

Fig. 1.

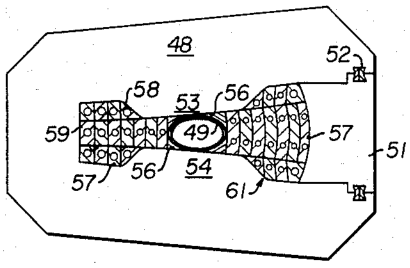

Fig. 4.

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HIGH ENERGY ACCELERATOR MAGNET STRUCTURE

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The invention described herein was made in the course of, or under Contract W–7405–Eng–48 with the United States Atomic Energy Commission.

The present invention relates to apparatus for accelerating charged particles to high energies and more particularly to the electromagnets used therein for the purpose of maintaining the particle beam in a substantially circular orbit. The invention provides a unique configuration for the magnet core and associated excitation coil which enables a more intense and broader magnetic field to be established in the beam region while reducing the amount of magnet material required.

Particle accelerators of the type which recirculate a particle beam around a curved path require a massive magnet structure to hold the beam in the desired orbit. In higher energy machines of this type particles are injected into the accelerator with considerable initial energy and the radius of the beam orbit is held almost constant, while the particles are gaining energy, by increasing the strength of the magnet field in the course of each accelerating cycle. Accordingly the magnet is ring-shaped in overall configuration. To facilitate construction of the magnet, and to provide a series of relatively unobstructed regions around the beam orbit, the magnet is usually comprised of a plurality of separate curvilinear sections or short straight sections some of which are spaced apart and connected by a linear vacuum tubulation through which the beam passes.

To effect optimum focussing of the circulating ion beam, recent accelerators of this type have frequently included magnets which provide an alternating gradient field. In particular, periodic ones of the magnet sections have a magnetic field, approximately normal to the plane of the particle orbit, in which the flux lines bow outwardly with respect to the center of the accelerator. In intervening ones of the magnet sections the flux lines have an opposite curvature. Any tendency of component particles to deviate from the preferred orbit is suppressed by passage of the beam through a series of such magnet sections, the theoretical basis for this strong focussing effect being understood within the art and being described, for example, by E. D. Courant et al., The Physical Review 88, 1190 (1952). This effect concentrates the beam at the desired orbit and allows a concomitant reduction of the cross-sectional area of the vacuum envelope and magnet structure.

Considering now the structure of an individual magnet section, it has heretofore been a common practice to make use of what is termed a C-magnet. The C-magnet has a core which, in cross-section, forms an incomplete annulus thus providing spaced apart pole pieces that define a field gap through which the beam passes. The exciting coil is generally split into two sections each encircling a separate one of two pole pieces. To provide the alternating gradient field configuration as hereinbefore described, the pole faces curve away from each other so that the field gap varies in height along an axis at right angles to the beam orbit whereby the desired bowing of the flux lines is established.

The magnet is the largest and most costly component of an accelerator of this type. Thus it is highly desirable that magnet design be optimized from the standpoint of providing a field of maximum strength and required cross-sectional area with a minimum investment in core and coil material. Advantages to be obtained by improved magnet design, over and above reduced material costs, are several. For a given output energy, the diameter of the accelerator and consequent real estate investment may be reduced and the problems of magnet alignment minimized. As the construction of a 200 b.e.v. accelerator having a diameter of the order of one mile is presently being planned, these cost factors are of over-riding importance in the art.

A serious limitation of prior accelerator magnet designs, of which the above described C-magnet is a representative example, arises from saturation effects. As discussed above, the magnet gap is of varying depth along an axis at right angles to the beam trajectory and thus the field is more intense at one side of the beam centerline than at the other. As a consequence the magnet iron reaches saturation at one side of the beam centerline at a time when the iron closer to the beam centerline is carrying considerably less than maximum flux. In a typical alternating gradient C-magnet formed of iron which saturates at a gap field strength of about 21 kilogauss this effect limits the maximum field in the region of the beam centerline to a conservative working value of about 12.5 kilogauss.

A closely related limitation of conventional magnet designs applies to the proportion of the total cross-sectional area of the magnet gap which can be used for transmitting beam. In order to provide alternating gradient focussing as discussed above, the field in the magnet gap must have a fairly specific curvature. In conventional accelerator magnets, the curvature of the pole faces that bound the gap is fixed to provide the necessary field configuration in the region of the theoretical beam centerline. However the field configuration becomes progressively less ideal away from the centerline. At some particular lateral distance from the centerline, the field ceases to have an adequate configuration and this defines the outer limit of the usable cross-sectional area of the gap.

Thus considerable advantage may be obtained if the magnet iron in the region of the beam centerline can be brought closer to saturation and if the desired field configuration can be maintained across a larger fraction of the magnet gap. The present invention provides a magnet construction which accomplishes both of these objectives.

The invention achieves these results by means of a specialized core and coil arrangement in which portions of the coil extend along each side of the field gap and form the lateral boundaries thereof. Each of the successive layers of turns which comprise these portions of the coil is formed to have a curvature conforming to the desired magnetic flux curvature within the region occupied by the layer of turns. In addition, the cross-sectional configuration of individual turns differ at differing regions of the coil in accordance with the particular desired current density for the regions of such turns. In this manner, the coil is utilized to establish a predetermined optimum field at each side of the gap. By thus forcing the field to have the desired configuration at the side of the gap, the coil arrangement causes the field to assume the preferred configuration throughout the gap.

Relative to conventional alternating gradient accelerator magnets, the above described coil arrangement draws flux from the narrow side of the gap towards the broader side thereof. As a consequence the field strength in the region of the beam centerline may more closely approach that of the saturated narrow side. Where iron saturating at a gap field of about 21 kilogauss is used as hereinbefore described, the field in the region of the beam centerline may now be about 18 kilogauss.

Accordingly it is an object of this invention to provide a more efficient magnet structure for use in charged particle accelerators.

It is another object of the invention to provide a charged particle accelerator magnet providing a stronger field in the beam aperture.

It is another object of the invention to provide a charged particle accelerator magnet having a broader usable beam aperture.

It is another object of this invention to reduce the initial investment costs of a very high energy particle accelerator.

It is another object of the invention to provide an accelerator magnet requiring substantially less iron and substantially less copper or other winding material to produce a specific field intensity at the beam orbit.

It is another object of the invention to provide a magnet construction permitting a reduction in the diameter of extremely high energy accelerators.

It is another object of the invention to reduce the difficulties of obtaining and maintaining magnet alignment in a high energy particle accelerator.

It is another object of the invention to provide a particle accelerator magnet in which maximum current density in the windings is confined to a small proportion thereof thereby reducing the costs and difficulties of powering and cooling the winding.

The invention, together with further objects and advantages thereof, will be better understood by reference to the following specification in conjunction with the accompanying drawing of which:

FIGURE 1 is a plan view of a portion of a high energy charged particle accelerator showing several sections of the magnet thereof together with certain of the associated accelerator components,

FIGURE 2 is a cross-section view of one of the magnet sections of the accelerator of FIGURE 1 taken along line 2—2 thereof,

FIGURE 3 is an end view of one of the magnet sections of FIGURE 1 taken along line 3—3 thereof, and

FIGURE 4 is a cross-section view of a second form of accelerator magnet embodying the invention.

Referring now to FIGURE 1 of the drawing, there is shown a section of a particle accelerator of the alternating gradient proton synchrotron class, the apparatus having an overall diameter of the order of one mile in order to provide for a maximum beam energy in the region of 200 b.e.v. The basic structure and principles of operation of an accelerator of this general type are known to those skilled in the art and therefore will be herein described only to the extent necessary for an understanding of the inclusion of the present invention therein.

Major elements of such an accelerator include a ring-shaped vacuum tubulation **11** through which the particle beam, indicated schematically by arrow **12**, is circulated, a magnet system **13** for constraining the beam to follow the desired orbit within tubulation **11**, and a beam accelerating station **14**. To provide for the positioning of additional components adjacent the beam orbit and to simplify such operations as beam injection, beam extraction and magnet alignment, the magnet system **13** is comprised of a large number of discrete magnet sections some of which may be spaced apart to leave relatively unobstructed straight sections along the beam orbit.

The representative portion of the accelerator illustrated in FIGURE 1 includes six magnet sections numbered **16**, **17**, **18**, **19**, **21** and **22** of which sections **16** and **17** are widely spaced to provide a long straight section for accelerating station **14** and magnetic beam focussing lenses **23**, sections **17** and **18** are spaced apart a shorter distance to provide for a vacuum pumping installation **24**, sections **18** and **19** are adjacent, sections **19** and **21** are spaced to provide a short straight section in which a subsequent beam focussing lens **26** is disposed, and sections **21** and **22** are also spaced to form a short straight section for an additional vacuum pumping installation **27**.

The beam focussing lenses **23** and **26**, which may be of the known type utilizing the focussing principles described in the Courant et al. reference hereinbefore identified, act upon a charged particle beam in a manner somewhat analogous to the action of an optical lens on a light beam and are provided to compensate for inaccuracies in machine construction and alignment and to compensate for the effect of introducing the field free straight sections along the beam orbit.

Elements of the accelerating station **14** include a cylindrical drift tube **28** which is disposed in alignment with tubulation **11** at a long gap therein and surrounded by an enlarged vacuum housing **29**. Drift tube **28** is spaced a small distance from the adjacent ends of tubulation **11**, forming a pair of accelerating gaps, and a frequency modulated radio frequency oscillator **30** is coupled to the drift tube to provide excitation therefor. Provided the frequency is properly matched to the other operating parameters of the accelerator in a manner understood with the art, circulating charged particles receive an increment of energy increase in crossing the gaps at the ends of the drift tube **28**.

Considering now the novel structure of a representative one of the magnet sections **19**, and with reference to FIGURE 2 in conjunction with FIGURE 1, a core assembly **31** encircles and defines a uniquely shaped field gap **32** through which the vacuum tubulation **11** extends, the core being formed of high permeability iron. To reduce power losses from eddy currents, core **31** is comprised of a large number of laminations or stacked plates **33** which may be held together by longitudinal through-bolts **34**.

The inner surfaces of the core assembly **31** which from the upper and lower boundaries of field gap **32** have similar but reversed hyperbolic curvatures so that, in cross-section, the gap is of greater height at one side of the beam orbit than at the other. Techniques for computing a precise curvature for the upper and lower boundaries of the field gap to achieve an alternating gradient focussing effect, given a specified set of accelerator parameters, are known in the art and thus will not be described herein. However as will hereinafter be discussed, the invention allows a stronger field at the beam orbit and a gap having a greater proportion of satisfactory field gradient area to be postulated as a basis for such computations.

An asymmetrically shaped electrical coil **36** is disposed in gap **32** to function as the energizing winding for core **31** and to perform the further function of establishing an optimum field configuration within the gap. Coil **36** consists of a plurality of series connected turns, twelve in this instance, formed of conductor **37** and disposed with opposite sides of the coil extending along the opposite sides of the gap **32**. The conductor **37** of coil **36** may be of copper and is hollow to provide a longitudinal passage **38** for coolant.

Coil **36** is shaped to fill the gap **32** except for the portions thereof occupied by vacuum tubulation **11** and the regions above and below the tubulation. To impart this shape to the coil **36**, the portions of the coil conductor at the broader side of the gap have broader cross-sectional dimensions than the continuations of the same turns at the opposite narrowed side of the gap. In addition, in this particular embodiment, the turns are arranged in two horizontal layers at the narrower side of the gap and in four horizontal layers at the opposite broader side, the number of vertically oriented layers of turns being correspondingly reduced at the broader side. The number of turns and the arrangement thereof into layers may be varied provided the divisions between turns and the overall form of the coil meet the conditions herein described.

Considering the shape of the coil **36** and the individual turns thereof still further, the outer surfaces of each portion of the conductor **37** are appropriately curved so that the more horizontal surfaces lie along magnetic equi-potential surfaces of the predetermined field within gap **32** and the more vertical conductor surfaces lie along flux lines of the field. This configuration inherently causes the outer surfaces of the coil as a whole to conform to the adjacent surfaces of core **31**. The configuration also results in the coil being essentially solid conductor throughout except for the coolant passage **38** and a thin layer of insulation **39** on the outer surfaces of the conductor **37**.

The described coil-conductor shape forces the field to approximate the desired predetermined configuration within the region occupied by the coil **36**. This in turn causes the field in the beam region, here represented by typical flux lines **40**, to assume the desired predetermined shape inasmuch as flux at the central region of a magnetic field must adjust itself in accordance with the flux curvature at the lateral portions of the field. This effect is supported by the variation in the cross-section of the coil conductor **37** which, in the described form, establishes a non-uniform current density in the coil that may be empirically determined to obtain the optimum magnetic field intensity at the corresponding region of gap **32**. Thus, for example, the coil **36** may have a lesser current density, and therefore generate a lesser field intensity, at the broader side of gap **32** than at the narrow side thereof if necessary to satisfy the field requirements for alternating gradient focussing.

Referring now to FIGURE 3 in conjunction with FIGURE 2, the portions of the conductor **37** of coil **36** at the ends of the magnet section **19** are curved to pass around the vacuum tubulation **11** and the two ends **41** of the coil conductor project laterally from the magnet for connection to a power supply as will hereinafter be described. To permit a flow of coolant to be circulated through the conductor, insulated inlet and outlet fittings **42** are disposed at the coil ends and communicate with the internal passages **38** thereof. Preferably, inlet and outlet fittings **42** are disposed at each end of each half turn section of conductor **37** to increase the total flow of coolant obtainable with a given supply pressure drop.

As shown in FIGURE 2 in particular, the novel magnet structure lends itself to a simple and convenient method of assembly. In particular, the core **31** is formed in two sections, of which the smaller section **43** is comprised of the portion of the core which spans the broader side of gap **32**. Core section **43** is secured to the remainder of the core by suitable keys **44** inserted longitudinally into grooves which extend along the boundaries between the two sections of the core.

Owing to the tapering cross-sectional configuration of the gap **32**, emplacement of the smaller core section **43** functions to secure all of the principal elements of the magnet in position in a rigid manner. Thus the core section **43** bears against the broader lateral surface of coil **36** thereby tending to wedge the coil into the gap **32**. To transmit such force evenly to the tubulation **11**, the spaces between the tubulation, core **31**, and the inner surface of coil **36** are filled by non-magnetic elements **45** formed of a radiation resistant material such as ceramic.

To effect alternating gradient focussing, the magnetic field gradient must be reversed at successive segments of the beam orbit, i.e. the flux which transects the orbit must bow towards the center of the accelerator at certain sections of the orbit and must bow outwardly at certain intervening portions of the orbit. By convention, the outwardly bowing portions of the field are designated by the letter F and the inwardly bowing field portions by the letter D. Field free gaps are designated by the letter O. Using this terminology, magnet section **19** as herein shown and described provides a D-field. To provide an F-field at appropriate segments of the orbit, a substantially identical magnet section is used, the magnet section being turned end to end so that the broader side of gap **32** is away from the center of the accelerator.

Thus, with reference again to FIGURE 1, magnet sections **16**, **19**, and **21** are arranged as hereinbefore described to provide a D-field and magnet sections **17**, **18** and **22** are turned endwise to provide F-fields. Taking into account the field free gaps previously described, the accelerator of FIGURE 1 thus has an FOFDOD field sequence, which sequence is periodically repeated around the beam orbit. As will be apparent to those skilled in the art, this is but one example of a suitable field sequence.

The magnet sections are connected in series with pulsed power supply **46** and, owing to the reversal of the F-magnet sections relative to the D-magnet sections, the conductor **47** which interconnects the coils of the magnet sections connects to the F-magnets at the forward ends thereof and to the D-magnets at the rearward ends thereby forming the non-uniform pattern of connections illustrated in FIGURE 1. Preferably, additional series connected magnet power supplies are provided around the circumference of the accelerator, each having a virtual ground connection, so that it is unnecessary to use high voltage for magnet excitation.

The invention consists essentially of disposing the excitation coil adjacent the sides of the field gap while forming the coil to force the field into a preferred configuration. As such it is not limited to the exact structure described above but may also be applied to differing magnet configurations. FIGURE 4, for example, illustrates an alternate embodiment which more closely resembles a conventional H-magnet but which also directly utilizes the windings to shape the field.

In the embodiment of FIGURE 4, as in the previous instance, a core **48** encircles a vacuum tubulation **49** which in turn encloses the beam orbit, the core being formed with a removable side section **51** held in place by keys **52**. In contrast to the first embodiment of the invention, salient upper and lower pole pieces **53** and **54** respectively are formed on the core **48** and project towards the tubulation **49**. The surfaces **56** of the pole pieces that are adjacent to tubulation **49** are formed with the hyperbolic curvature hereinbefore described.

This configuration provides relatively larger spaces **57** at the sides of the field gap **58** in which relatively more coil conductor **59** may be disposed. Thus, relative to the previous embodiment, lower current density and thus less cooling capacity is required thereby reducing operating costs. However somewhat more copper and magnet iron is required so that the initial costs of the accelerator are higher.

As in the first described embodiment, the conductor **59** which forms the coil **61** is of non-uniform cross-section with a first pair of outer surfaces formed to lie along magnetic equi-potential surfaces of the field and with the transecting pair of outer conductor surfaces curved to follow the flux lines of the field. The innermost portions of the coil **61** at each side of the field gap **58** extend a small distance between pole pieces **53** and **54**. The coil thus directly influences the shape of the field in gap **58** in a manner similar to that hereinbefore described.

It will be apparent that still other variations are possible within the spirit and scope of the invention and thus it is not intended to limit the invention except as defined in the following claims.

What is claimed is:

1. In a magnet for guiding a charged particle beam within a particle accelerator, the combination comprising a ferromagnetic core having spaced apart pole pieces forming a gap through which said beam passes, said gap having a differing depth at opposite sides of the beam trajectory whereby the magnetic flux between said pole pieces is bowed with respect to said beam trajectory, and an excitation coil having sections extending along opposite sides of said gap, said sections being of differing height corresponding to said difference in depth of opposite sides of said gap and having surfaces which are bowed in correspondence with the curvature of said magnetic flux in the region of said surfaces.

2. A magnet for a charged particle accelerator as described in claim **1** wherein said coil is comprised of a plurality of turns and wherein said turns are of greater cross-sectional area at the high side of said gap relative to the narrow side thereof.

3. A magnet for a charged particle accelerator as described in claim **1** wherein the surfaces of said coil sections adjacent said pole faces have a curvature corresponding to that of said pole faces.

4. In a charged particle accelerator, a beam guiding magnet sector comprising, in combination, a ferromagnetic core having a beam passage therethrough with opposed surfaces of said passage forming pole faces, and an excitation coil for said core having sections extending along the sides of said passage between said pole faces, said coil sections being formed of a plurality of turns of conductor with opposite surfaces of the turns of conductor having curvatures conforming to predetermined curvatures for magnetic flux in the region of said surfaces.

5. A magnet for a charged particle accelerator comprising a ferromagnetic core element transpierced by a particle beam passage having opposed pole face surfaces of substantially hyperbolic cross-section whereby said passage is of greater height at a first side of the beam trajectory than at the opposite side thereof, and an asymmetric winding for said core having sections extending along opposite sides of said passage and extending between said pole face surfaces whereby said winding is of greater height at said first side of the beam trajectory than at the opposite side thereof, said winding sections having inner surfaces which are curved in conformity with the curvature of the adjacent portions of the magnetic field within said passage.

6. A magnet for a charged particle accelerator as described in claim **5** wherein said winding is comprised of a plurality of turns of conductor and wherein the divisions between successively more lateral layers of said turns have progressively changing curvatures in order to lie along the flux lines of said magnetic field.

7. In a charged particle accelerator of the class having an evacuated curvilinear tubulation through which the particle beam orbit passes, a magnet structure comprising a ferromagnetic core enclosing said vacuum tubulation and having pole face surfaces at opposite sides thereof for establishing a magnetic field therethrough, said pole face surfaces being divergent with respect to the plane defined by said particle beam orbit whereby said magnetic field has a gradient in the region of said vacuum tubulation, an asymmetrically shaped winding having sections extending within said core along opposite sides of said vacuum tubulation with each section spanning the gap between said pole faces, the surfaces of said winding sections which are adjacent said pole faces being shaped to conform thereto and the inner surfaces of said winding sections which face said vacuum tubulation being shaped to follow a predetermined curvature for said magnetic field in the region of said inner surfaces, and a pulsed direct current power supply coupled to said winding.

8. A charged particle accelerator magnet structure as described in claim **7** wherein said winding is comprised of a plurality of turns of conductor and wherein said conductor has varying cross-sectional dimensions at differing regions of said winding to establish a predetermined current density distribution within the region occupied by said winding.

9. A charged particle accelerator magnet structure as described in claim **7** wherein said winding is comprised of a plurality of turns of conductor which has changed dimensions at successive segments thereof, the conductor having a first pair of opposite lateral surfaces with a curvature conforming to that of the adjacent magnetic field and having a second pair of opposite lateral surfaces curved to follow magnetic equi-potential surfaces of said field.

10. A charged particle accelerator magnet structure as described in claim **7** wherein said ferromagnetic core is formed of two discrete elements, a first of said elements being comprised of the portion of the core which extends between said pole faces at the more widely spaced side thereof and comprising the further combination of clamping means securing said elements together as an integral unit.

11. A charged particle accelerator magnet structure as described in claim **10** comprising the further combination of spacer material filling the regions between said vacuum tubulation and said winding sections whereby said first core element and said clamping means may be utilized to maintain a wedging pressure on said winding to bind the core and winding and vacuum tubulation into a rigid unit.

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