Dec. 21, 1965 N. F. VERSTER ETAL 3,225,270

POLE SHOE ASSEMBLY FOR A CYCLOTRON ELECTROMAGNET

Filed April 15, 1963 4 Sheets-Sheet 1

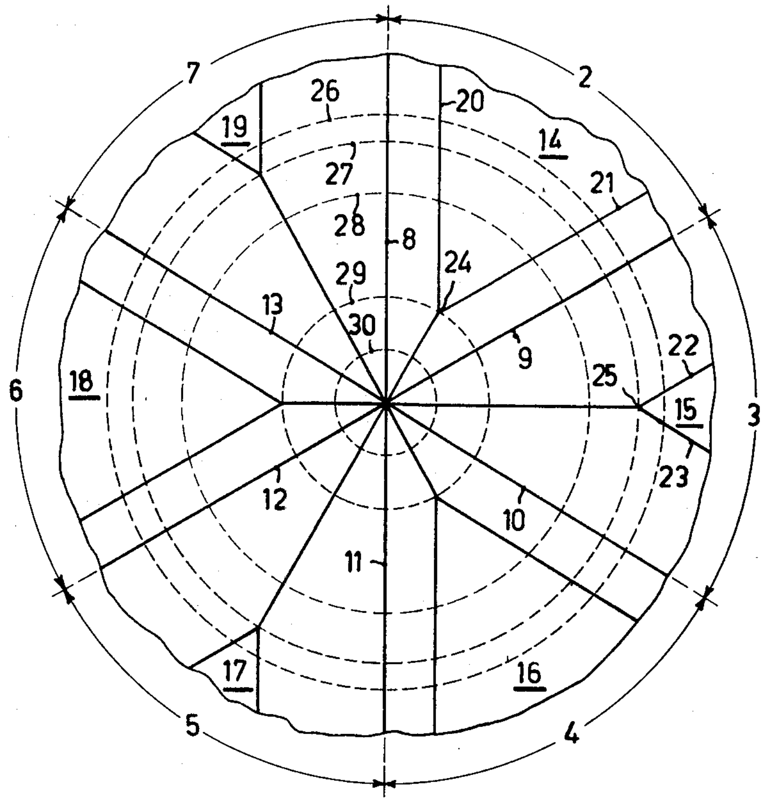

FIG.1

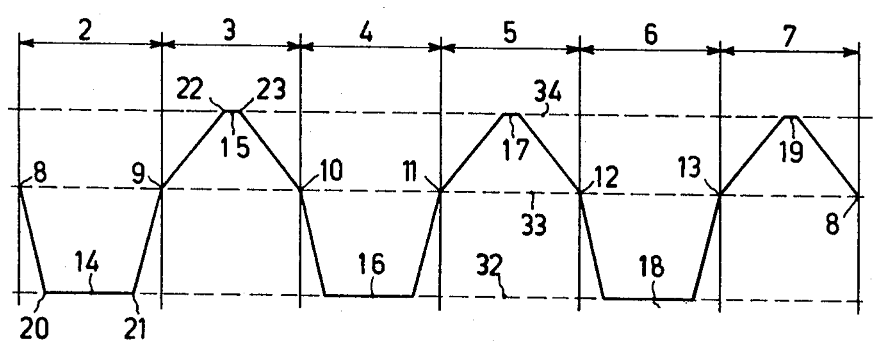

FIG.2

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POLE SHOE ASSEMBLY FOR A CYCLOTRON ELECTROMAGNET

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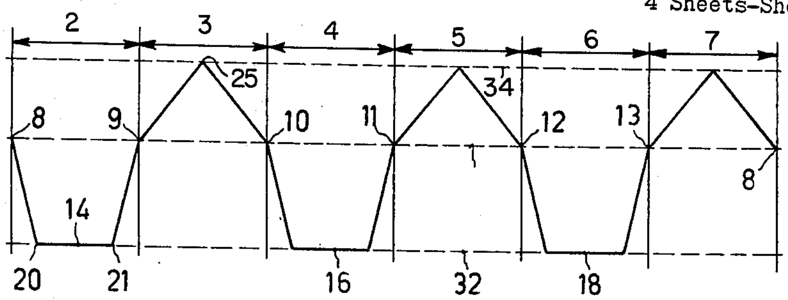

FIG.3

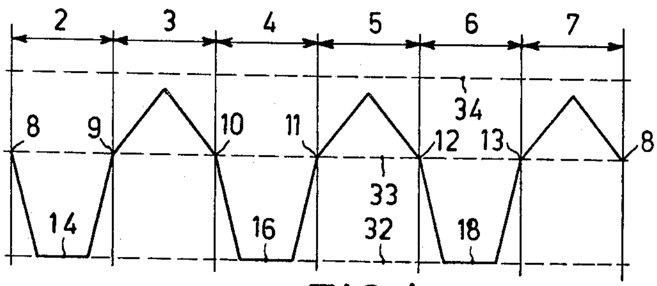

FIG.4

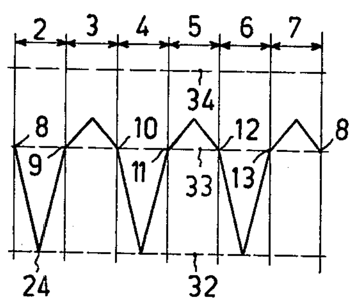

FIG.5

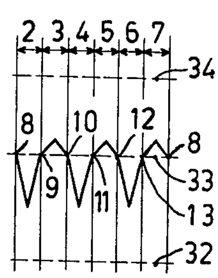

FIG.6

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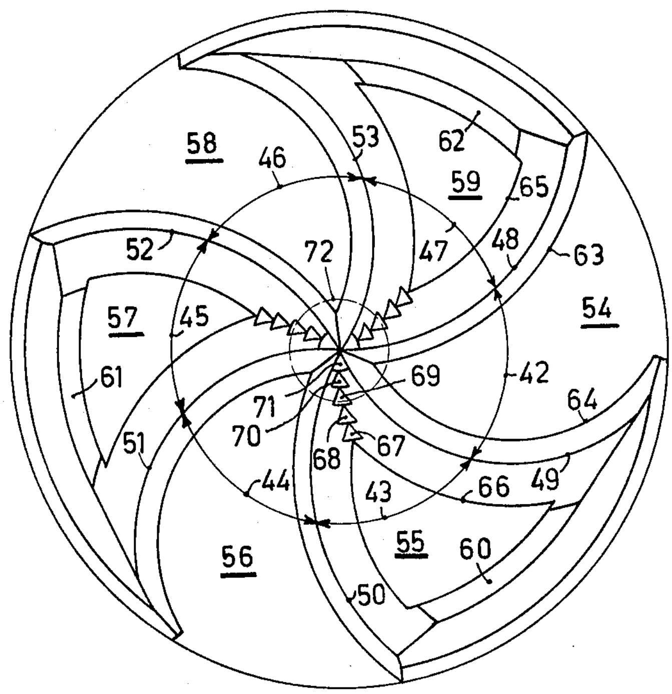

FIG. 7

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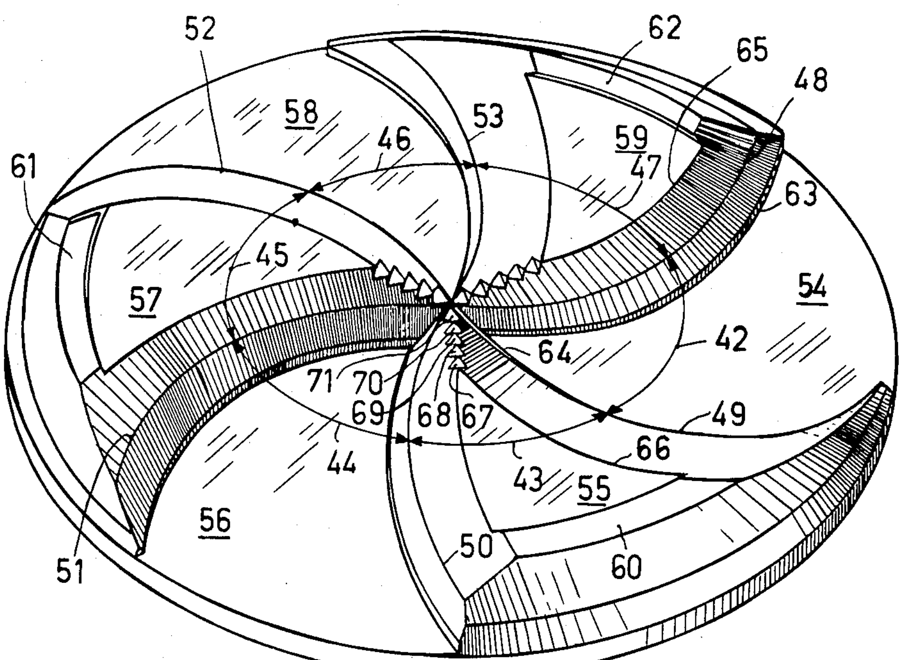

FIG.8

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POLE SHOE ASSEMBLY FOR A CYCLOTRON ELECTROMAGNET

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Claims priority, application Netherlands, Apr. 16, 1962, 277,304
3 Claims. (Cl. 317—158)

The invention relates to an electromagnet for use in a cyclotron, in which at least in the central part the axial stability of the particles is improved by azimuthal dependence of the magnetic flux by means of two pole shoes, each having the same number of segments of alternately great and small heights, said pole shoes being arranged so that the segments of great height, as well as the segments of small height are opposite one another, the difference in height between a segment of great height and a segment of small height being substantially zero at the center of the pole shoes.

In a cyclotron charged particles are accelerated. Cyclotrons may be of different designs. The various kinds of cyclotrons may be explained as follows.

The period of one revolution of a particle accelerated in a so-called classical cyclotron is:

$$\frac{2\pi m}{eB} \text{ sec.}$$

wherein m is the mass of the particle, e the charge thereof and B the flux density. For obtaining a stable, axial movement it is necessary for the flux density to decrease in a radial sense. The period of revolution increases with an increasing radius. The increase in velocity of the particle involves an increase in its mass, which results in an increase in the period. The increase in the period of revolution of the particle gives rise to an out-of-phase relationship to the alternating voltage at the acceleration electrodes, so that finally a deceleration may occur. Consequently, the particle can be accelerated only a restricted number of times, so that the attainable energy is limited.

In a synchrocyclotron this disadvantage is obviated by modulating the frequency of the alternating voltage at the acceleration electrodes so that the particle can perform the orbit "in synchronism" with the electric field. Thus the particles are accelerated in groups. Since the modulation of the alternating voltage at the acceleration electrodes can be adapted only to one given group of particles, the number of accelerated particles is low as compared with that of the classical cyclotron.

In an isochroncyclotron the aforesaid drawback is mitigated in a different way, which does not involve the disadvantage of a restriction of the number of accelerated particles. In contradistinction to a classical cyclotron and a synchrocyclotron, where the magnetic field is, in principle, azimuthally constant, the magnetic field in an isochroncyclotron depends upon the azimuth so that the movement of the particles is axially stable, whereas nevertheless the mean value of the flux density along the paths increases in a raidal direction, so that the orbital period remains constant. In the formula given above B designates the mean value of the flux density along a path. Whereas in a classical cyclotron the flux density decreases in a radial direction in order to obtain a stable, axial movement of the particle, so that the effect thereof on the orbital period of the particle and the effect of the increase in velocity co-operate with each other, the mean value of the flux density in an isochroncyclotron increases in a radial direction, so that the two effects mentioned above

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counteract each other and a constant orbital period can be obtained. The azimuthal variation of the magnetic field can be produced by means of a particular configuration of the surface of the pole shoe of the magnet. To this end the pole shoes are divided into the same number of segments of alternately great and small heights. By providing, in a radial direction, an increasing extension of the segments of great height in the azimuthal sense and a decreasing extension of the segments of small height, the mean value of the flux density along the paths will increase in radial direction. This involves the disadvantage that near the center the difference in height between a segment of great height and a segment of small height is high as compared with the width of a segment, so that only a very small portion of a segment of small height operates effectively as a magnet pole. The by far larger part of the magnetic lines of force then concentrates in a portion which, in practice, is usually about half of the available surface of the poles, so that at the center the pole shoe is saturated at a lower value of the magnetic flux in the acceleration range of the particles than in the part lying further to the outside.

With pole shoes in which in a radial direction the azimuthal extension of the segments remains unchanged, an increase in the mean value of the flux density along the paths can be obtained in a radial direction by means of an increase in height of the segments of great height in said direction and by means of a decrease in height of the segments of small height. A pole shoe for such a device is described e.g. in "The Review of Scientific Instruments," vol. 29, No. 7, page 662, July 1958, and in Khoe Kong Tat's Thesis, pages 72 and 73, Delft 1960. This pole shoe will be described more fully. Each segment has an angular aperture of 45°; starting from the center, in a radial direction, the height of the segment of great height increases stepwise and the height of the segment of small height decreases stepwise. At the center the segments join each other at a point or a small surface. The segments are separated by vertical planes and the right angles between such a plane and the plane of a segment of great height gives rise to an excessive concentration of the magnetic lines of force, so that at the said area the magnetic material is saturated at a lower value of the magnetic flux in the acceleration region of the particles. This brings about high different shapes of the magnetic field with different values of the magnetic flux. Segments of this kind are only suitable for a given magnetic flux. In the publications referred to above it is illustrated that the right angles between the planes of the segments of great height and the vertical planes of separation are slightly beveled over a portion lying beyond the central region.

The invention relates to an electromagnet for use in a cyclotron in which at least in the central part an axial stability of the particles is improved by azimuthal dependence of the magnetic flux. The central part of an electromagnet is to denote herein a surface the center line of which is approximately equal to the distance between the pole shoes at the center. Owing to the azimuthal dependence of the magnetic flux in the central region the axial stability of the particles is improved in said region. The electromagnet comprises two pole shoes each having an equal number of segments of alternately great and small height, said pole shoes being arranged so that the segments of great height, as well as the segments of small height are opposite one another. The pole shoes have furthermore the feature that at the center the difference in height between a segment of great height and a segment of small height is substantially zero. At the center the magnetic flux must be substantially equal to the mean magnetic flux density on a circle in the central region. According to the prior art the surface of a pole shoe may be constructed to this end so that this is the case for a given average magnetic flux density. Said configuration of the pole shoe in the central region may be used in the three clyclotrons mentioned above: the classical cyclotron, the synchrocyclotron and the isochroncyclotron. The disadvantage is that in this case the cyclotrons are adapted to a given magnetic flux only, so that the particles can only be accelerated to a given energy.

The invention relates to a configuration of the pole shoes in the central region of the electro-magnet such that it applies to different magnetic flux densities that the value thereof at the center is substantially equal to the mean value across a circle in the central region. In accordance with the invention the surface of the pole shoes in the central region along the paths covered by the particle is such that the difference between the greatest height and the height at the center is smaller than the difference between the height at the center and the smallest height, that the variation of the level of the greatest height and that of the height at the center is, on an average, less steep than the variation between the level of the height at the center and that of the smallest height and that the variation between the level of the greatest height and that of the height at the center is, on an average, at an angle of between 20° and 90° to the direction of the axis of the electro-magnet and the variation between the level of the height at the center and that of the smallest height is, on an average, at an angle of between 10° and 90° to the direction of the axis of the electro-magnet. It is thus achieved at the same time that away from the center in a radial direction the difference in height of the segments of great and small heights varies strongly, which is important for obtaining the desired axial stability without the occurrence of an additional great magnetic saturation at different parts of the surface of the pole shoes, which would involve a restriction to a given average flux density. The variation between the level of the greatest height and that of the height at the center is preferably, on an average, at an angle of at least 60° to the direction of the axis of the electro-magnet and the variation between the level of the height at the center and that of the smallest height is, on an average, at an angle of at least 35° to the direction of the axis of the electro-magnet.

The embodiment of the invention is particularly employed in an electro-magnet for use in an isochroncyclotron, since herein an azimuthal dependence of the magnetic field is available for obtaining an axial stability of the particles. The segments of great and small heights at the center change into those located in the regions of the pole shoes farther to the outside.

The segments form in particular lines of separation of constant height. This is of course the same height as that at the center. This implies a structural advantage, since the configuration of the surface described above can be fixed in a simple manner.

The segments need not be straight. They may be spiral-shaped. This is particularly desirable in order to improve the axial focusing in the region beyond the center, so that a smaller field modulation may suffice. For practical reason the segments at the center are constructed in said manner, although this is not required.

If the pole shoe comprises regions of maximum height and minimum height, it will be advantageous in practice to compose the pole shoe from a base plate and portions, the shape of which corresponds to a segment of great height and the adjacent parts of the segments of small height, the height of which exceeds the minimum height. Thus the base plate forms the parts of minimum height of the segments of small height.

The invention furthermore relates to a pole shoe for use in such an electro-magnet, said pole shoe comprising an even number of segments of alternately great and small height, the difference in height at the center between a segment of great height and of segment of small height being substantially zero. The surface of the pole shoe at the center along the paths covered by the particles is then such that the difference between the greatest height and the height at the center is smaller than the difference between a height at the center and the smallest height, that the variation between the level of the greatest height and that of the height at the center is on an average less steep than the variation between the level of the height at the center and that of the smallest height and that the variation between the level of the greatest height and that of the height at the center is on an average at an angle of at least 20°, preferably at least 60° to the direction of the axis of the electromagnet and the variation between the level of the height at the center and that of the smallest height is on an average at an angle of at least 10°, preferably at least 35° to the direction of the axis of the electromagnet.

The invention furthermore relates to a device for accelerating particles of the cyclotron type, comprising an electro-magnet having the said features. In such a device particles can be accelerated to different energies by a variation of the magnetic flux. A device for accelerating particles of the cyclotron-type is to denote not only a classical cyclotron but also a synchrocyclotron and an isochroncyclotron.

Embodiments of the pole shoe according to the invention will be described more fully with reference to the drawing.

FIG. 1 is a plan view of the control region of a pole shoe.

FIGS. 2, 3, 4, 5 and 6 are azimuthal sections taken on different circles at right angles to the plane of the drawing of FIG. 1. The scale of FIGS. 2, 3, 4, 5 and 6 is the same, but it is smaller with respect to that of FIG. 1.

FIG. 7 is a plan view of a pole shoe for use in an isochronocyclotron, the central region of which is constructed in accordance with the invention.

FIG. 8 is a perspective view of the pole shoe illustrated in FIG. 7.

The central region of the pole shoe of FIG. 1 comprises six segments, i.e. the segments **2**, **4** and **6** of small height and the segments **3**, **5** and **7** of great height. These segments constitute the lines of separation **8**, **9**, **10**, **11**, **12** and **13** respectively. The segments of small height **2**, **4** and **6** comprise parts of minimum height **14**, **16** and **18** respectively; the segments of great height **3**, **5** and **7** comprise parts of maximum height **15**, **17** and **19** respectively. The lines **20** and **21** are the boundary lines of the region of minimum height **14**. They intersect each other at **24**. The lines **20** and **8** and the lines **21** and **9** are equidistant. The lines **22** and **23** are the boundary lines of the region of maximum height **15**. They intersect each other at **25**. The lines **22** and **9** and the lines **23** and **10** are equidistant. The same applies to the boundary lines and the other regions of minimum height and maximum height.

FIG. 2 shows the upper part of the azimuthal section taken on the circle **26** at right angles to the plane of the drawing of FIG. 1. The upper surface of the pole shoe extends in the segment **2** from the point of intersection of the line of separation **8** towards the point of intersection of the boundary line **20** of the region of minimum height **14** and this minimum height is maintained up to the point of intersection of the other boundary line **21**. From said point of intersection it extends towards the point of intersection with the line of separation **9** with the adjacent segment of great height **3**. In this segment the upper surface extends towards the point of intersection of the boundary line **22** of the region of maximum height **15**, which maximum height is maintained up to the point of intersection of the other boundary line **23**. From said point of intersection it extends towards the point of intersection with the line of separation **10** with the adjacent segment of small height. The broken line **32** indicates the level of the minimum height, the broken line **33** indicates that of the height of the lines of separation and the broken line **34** indicates that of the maximum height. The further reference numerals have the same meaning as those of FIG. 1.

FIG. 3 shows the upper part of the azimuthal section taken on the circle **27** at right angles to the plane of the drawing of FIG. 1. In this circle the parts of maximum height are reduced to a point, as is indicated for the segment **3** by **25**. The description of this figure may furthermore be derived from that of FIG. 2.

FIG. 4 shows the upper part of the azimuthal section taken on the circle **28** at right angles to the plane of the drawing in FIG. 1. In this circle there are no parts of maximum height. The description of this figure may be derived from that of FIG. 2.

FIG. 5 shows the upper part of the azimuthal section taken on the circle **29** at right angles to the plane of the drawing of FIG. 1. In this circle the parts of minimum height are reduced to a point, which is indicated for the segment **2** by **24**. The description will furthermore be clear from that of FIG. 2.

FIG. 6 shows the upper part of the azimuthal section taken on the circle **30** at right angles to the plane of the drawing of FIG. 1. In this circle there are no longer any parts of minimum height. The description of this figure will be evident from that of FIG. 2.

FIG. 7 is the plan view of a pole shoe for use in an isochroncyclotron, the central part of which is constructed in accordance with the invention. The pole shoe comprises six segments, i.e. the segments **42, 44** and **46** of small height and the segments **43, 45** and **47** of great height. Said segments form the lines of separation **48, 49, 50, 51 52** and **53** respectively. The segments of small height **42, 44** and **46** comprise parts of minimum height **54, 56** and **58** respectively; the segments of great height **43, 45** and **47** comprise, apart from the higher edges, **60, 61** and **62** respectively, parts of maximum height **55, 57** and **59** respectively. The lines **63** and **64** are the boundary lines of the region of minimum height **54**. The line **65** is a boundary line of the region of maximum height **59** and the line **66** is a boundary line of the region of maximum height **55**. Towards the center the variation of the level of the maximum height towards the level of the height of the lines of separation is a stepwise variation. This implies that the mean magnetic field approaches slightly further the ideal form. This provides, in addition, the practical advantage that a platform is obtained, on which a box-shaped ion source can easily be disposed. For the segment **43** the variation of the level of maximum height **55** towards the center extends via the parallel faces **67, 68, 69, 70** and **71**. The height of the face **71** is equal to that of the lines of separation. The face **71** constitutes with the corresponding faces of the segments **45** and **47** the platform on which the box-shaped ion source can be disposed. From the drawing it will be seen that the segments are spiral-shaped. The lines **63, 48** and **65** are parts of circles. The centers of said circles are located on one line, which is at right angles to the plane **54**. The lines **64, 49** and **66** are also parts of circles and the centers thereof are also located on one line which is at right angles to the plane **54**. The same applies to the similar lines of the pole shoe.

In a given embodiment of this pole shoe of mild steel there is a radius of 65 cms. The lines of separation of a region of great height (for example **53** and **48**) intersect each other at the center at an angle of 55°. The difference in height between the regions of maximum height and the lines of separation is 2.5 cms. and the difference in height between the lines of separation and the regions of minimum height is 5 cms. The line **63** is associated with a circle having a radius of 49.1 cms. and the line **64** is associated with a circle having a radius of 33.06 cms. In the azimuthal direction the variation of the region of maximum height **55** towards the line of separation **49** is at an angle of 70° 30′ to the direction at right angles to the plane **55**, whereas the variation of the line of separation **49** towards the region of minimum height **54** is at an angle of 42° to the direction at right angles to the plane **54**. The difference in height between the region of maximum height **55** and the faces **67, 68, 69, 70** and **71** is 0.5 cm. each.

Such a pole shoe can be built up in a simple manner from a base plate, with which are associated the parts **54, 56, 58**, and three identical sectors. The shape of each sector corresponds to a segment of great height and the adjacent parts of the segments of small height, which have a height exceeding the minimum height. Each sector has an angle of 120° at the center of the pole shoe.

In the disposition in the electro-magnet the distance between the pole shoes at the center is 20 cms. The central region is to denote the part having a radius of 10 cms. This region is located inside the circle **72**. It has been assessed that by means of such a cyclotron magnetic fields of the desired shape can be obtained up to a magnetic flux density at the center of 15,500 gauss.

We claim:

1. A pole shoe assembly for a cyclotron electromagnet in which at least in the central region the axial stability of the particles is improved by azimuthal dependence of the magnetic flux, comprising a pair of opposed pole-shoes each having the same number of segments of alternately large and small heights which are positioned relative to one another so that the segments of large height, as well as the segments of small height, are opposite one another, and with a given axis passing through the center of each pole-shoe, the difference in height between a segment of greater height and a segment of smaller height being substantially zero in the vicinity of the center of each shoe, the difference between the greatest height and the height at the center of each pole-shoe being smaller than the difference between the height at the center and the smallest height, the variation between the level of greatest height and that of the height at the center being less steep than the variation between the level of the height at the center and the smallest height, the variation between the level of the greatest height and that of the height at the center being at an angle between 20° and 90° to said axis, and the variation between the level of the height at the center and that of the smallest height being at an angle between 10° and 90° to said axis.

2. A pole shoe assembly for a cyclotron electromagnet in which at least in the central region the axial stability of the particles is improved by azimuthal dependence of the magnetic flux comprising a pair of opposed pole-shoes each having the same number of segments of alternatively large and small heights and being positioned relative to one another so that the segments of large height, as well as the segments of small height, are opposite one another, and with a given axis passing through the center of each pole-shoe, the difference in height between a segment of greater height and a segment of smaller height being substantially zero in the vicinity of the center of each shoe, the difference between the greatest height and the height at the center of each pole-shoe being smaller than the difference between the height at the center and the smallest height, the variation between the level of greatest height and that of the height at the center being less steep than the variation between the level of the height at the center and the smallest height, the variation between the level of the greatest height and that of the height at the center being at an angle between 60° and 90° to said axis, and the variation between the level of the height at the center and that of the smallest height being at an angle between 35° and 90° to said axis.

3. A pole shoe assembly for a cyclotron electromagnet in which at least in the central region the axial stability of the particles is improved by azimuthal dependence of the magnetic flux comprising a pair of opposed pole-shoes each having the same number of segments of alternately large and small heights and being positioned relative to one another so that the segments of large height, as well as the segments of small height, are opposite one another, said segments of large height being bounded by lines which intersect at the center of each pole piece and form an angle of about 55° therebetween, said pole-shoes defining a given axis passing through the center of each pole-shoe, the difference in height between a segment of greater height and a segment of smaller height being substantially zero in the vicinity of the center of each shoe, the difference between the greatest height and the height at the center of each pole-shoe being smaller than the difference between the height at the center and the smallest height, the variation between the level of greatest height and that of the height at the center being less steep than the variation of the level of the height at the center and

the smallest height, the variation between the level of the greatest height and that of the height at the center being at an angle of between 20° and 90° to said axis, and the variation between the level of the height at the center and that of the smallest height being at an angle of between 10° and 90° to said axis.

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