July 16, 1968 G. T. DANBY ETAL 3,393,385

QUADRUPOLE MAGNET WITH REDUCED FIELD DISTORTION

Filed Aug. 24, 1966 2 Sheets-Sheet 1

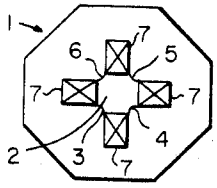


Fig. 1

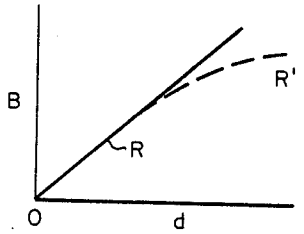


Fig. 2

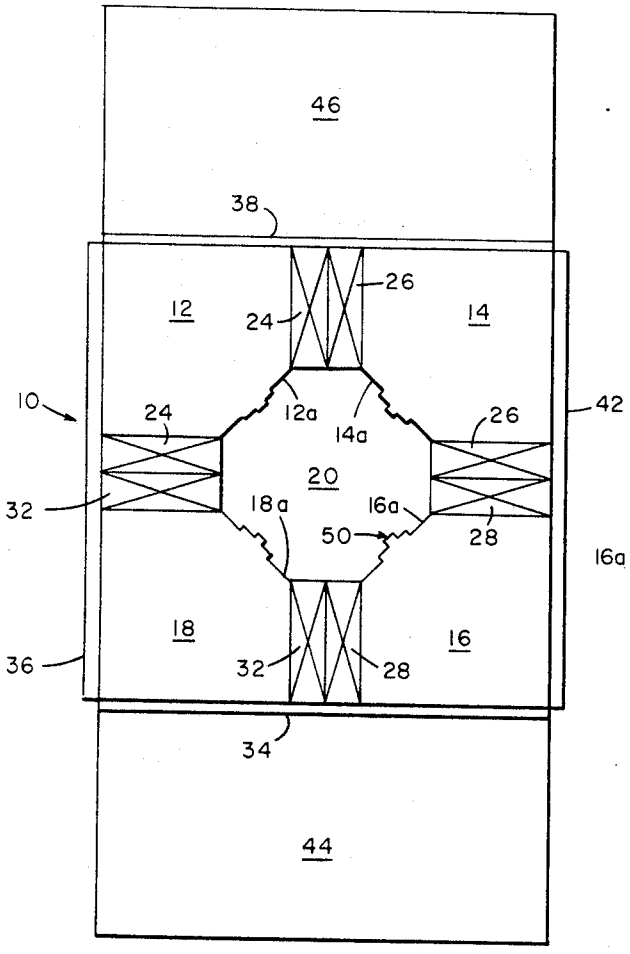


Fig. 3

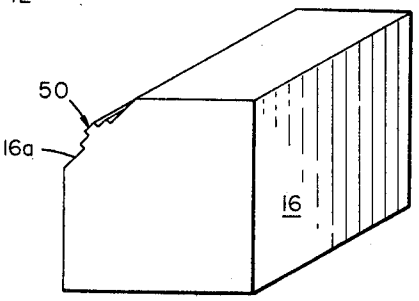


Fig. 3a

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July 16, 1968 G. T. DANBY ETAL 3,393,385

QUADRUPOLE MAGNET WITH REDUCED FIELD DISTORTION

Filed Aug. 24, 1966 2 Sheets-Sheet 2

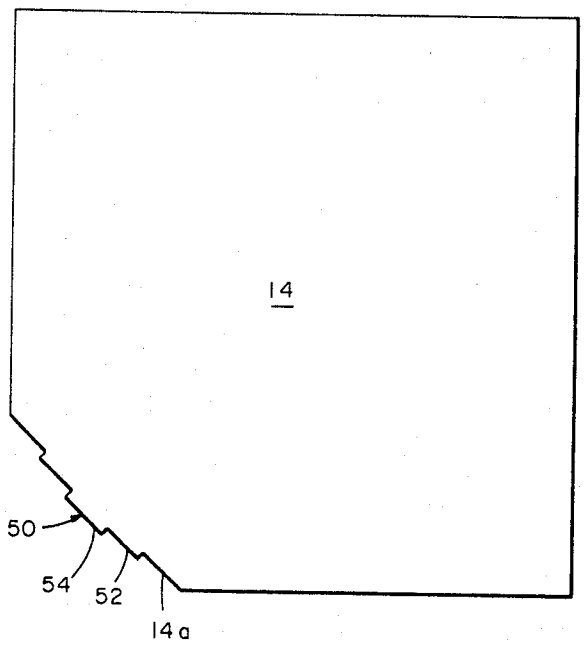


Fig. 4

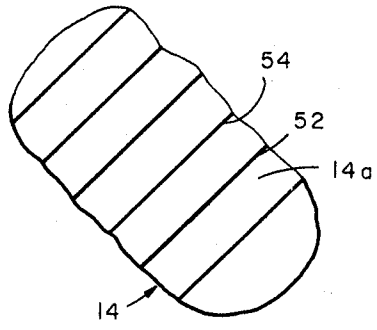


Fig. 5

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QUADRUPOLE MAGNET WITH REDUCED FIELD DISTORTION

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ABSTRACT OF THE DISCLOSURE

A quadrupole magnet using pole pieces which are largely rectangular in configuration utilizing protrusions on the faces thereof to reduce down to acceptable values any non-linearities and undesirable harmonics which may occur.

The invention described herein was made in the course of, or under a contract with the U.S. Atomic Energy Commission.

Background of the invention

The Alternating Gradient Synchrotron (AGS) located at the Brookhaven National Laboratory utilizes a series of combined function quadrupole focusing and dipole bending magnets to keep the proton beam focused and bent around a circular path.

The purpose of a quadrupole magnet is to focus beams of charged particles. A single quadrupole magnet focuses particles in one plane and defocuses them in a plane perpendicular to the focusing plane. However, a pair of quadrupoles with their focusing planes alternated can be set up to focus in all planes.

In our U.S. Patent No. 3,284,744, issued Nov. 8, 1966, entitled "Quadrupole Magnet with Reduced Lateral Dimension" we presented an improved quadrupole magnet construction which makes it possible to utilize quadrupole magnets for the purpose of taking away from the primary proton beam path secondary particles at an angle which is smaller than was previously possible due to reduced lateral dimension of the magnet covered in the mentioned application.

Another important problem presented in the design of a quadrupole magnet is that of eliminating, or minimizing, harmonic effects and that of reducing to acceptable values non-linearities in the magnetic field. Heretofore, this problem has largely been overcome by calculating with elaborate mathematic techniques a magnet profile of quite complex shape which requires a special die to punch the quadrupole magnets to the shape desired. Where a large number of identical magnets are required for a specific situation the cost of the die is spread over the large number of magnets prepared, but, when, as in the usual case a relatively small number of magnets is to be made, the cost attributed to make each magnet becomes very high. In addition, the special profile tends to limit to a narrow range the use of the magnet whereas a quadrupole for more general use may be desirable so that it can be used under a greater variety of conditions.

Description of the invention

The present invention overcomes the disadvantages associated with the use of the profiled magnet by producing a magnet which can be machined readily to obtain an approximation of the shape desired and incorporates specific features designed to reduce down to acceptable values any non-linearities and undesirable harmonics which may occur.

In this invention it is accomplished by using pole pieces which are largely rectangular in configuration and are provided with appropriate protrusions to reduce or eliminate the undesirable effects noted above.

It is thus a principal object of this invention to provide a quadrupole magnet of simple shape utilizing protrusions to reduce harmonics and non-linearities in the magnetic field.

Other objects and advantages of this invention will hereinafter become readily apparent from the following description of a preferred embodiment of this invention taken with respect to the accompanying drawings in which:

FIG.1 is an elevation view of a conventional quadrupole magnet such as those used in the AGS;

FIG. 2 is a graph of magnetic field intensity versus distance from the center of the air space in a quadrupole magnet;

FIG. 3 is an elevation view of a quadrupole magnet embodying the principles of this invention;

FIG. 3*a* is an isometric view of a magnetic pole shown in FIG. 3;

FIG. 4 is a detailed view of a magnet pole piece used in the magnet of FIG. 2; and

FIG. 5 is a view showing the face of the pole piece of FIG. 4.

Referring to FIG. 1 there is illustrated a conventional quadrupole magnet assembly **1** having an air space **2** and curved pole faces **3**, **4**, **5** and **6** and coils **7** schematically illustrated. The purpose of the curved pole faces is to reduce the harmonic content of magnet **1**. In the ideal magnet the curved faces of the magnet pole pieces **3**, **4**, **5** and **6** would come together tangentially. However, as is illustrated, room must be left for coils **7** passing between adjacent pieces. Thus, as shown in FIG. 2 what should be an ideal straight line curve R representing the intensity B of the magnetic field as a function of the distance *d* from center O of air space **2** within quadrupole **1**, actually droops and forms a curve R' as the pole faces are approached. This droop can be considered from a mathematical point of view as being caused by harmonics so that by minimizing the harmonic terms in the equations for the magnetic field the drooping can be minimized to an acceptable level.

In accordance with this invention it is possible to minimize this harmonic effect without resorting to elaborately designed magnetic pole pieces. Referring to FIG. 3, quadrupole magnet **10** shaped in accordance with this invention consists of pole pieces **12**, **14**, **16** and **18** assembled in the square array as shown to form an air gap **20** and pairs of copper windings **24**, **26**, **28** and **32** wrapped around pole pieces **12**, **14**, **16** and **18** respectively. Structural members **34**, **36**, **38** and **42** of iron material hold pole pieces **12–18** together, while iron yokes **44** and **46** are assembled as shown to complete the necessary magnetic circuits as described in our previously mentioned patent application. Pole pieces **12–18** have the shape shown for piece **16** illustrated in FIG. 3*a*.

Each of the pole pieces **12**, **14**, **16** and **18** is provided with a pole face **12***a*, **14***a*, **16***a* and **18***a*, respectively, which is a flat surface on which a plurality of bumps or protrusions **50** are formed.

Referring to FIGS. 4 and 5 for a more particular description of protrusions **50**, there is illustrated pole piece **14** with pole face **14***a* on which a pair of stepped protrusions **52** and **54** are formed. It was found that the use of such bumps or protrusions on the pole faces can be used successfully to suppress harmonics and that it was unnecessary to go to the more elaborate curvatures of the faces themselves as has been thought to be the case up to now. The protrusions extend the whole depth of each pole face and are symmetrical across the width of the pole face.

It was determined that the shape of protrusions **52** and **54** was not critical but cross-sectional surface areas are, and also it was necessary to have the protrusion surfaces parallel to that of the pole faces. Hence, simple rectangular protrusions, readily machinable, may be used to obtain the improved magnet characteristics. Protrusions **52** and **54** extend along the whole length of piece **14** as indicated for piece **16** in FIG. 3*a*.

The use of steps or protrusions **52** and **54** tend to cancel the effect of having the spaces between adjoining pole pieces to accommodate the coils necessary to establish the magnetic fields; and by trying different size protrusions it is possible to bring curve R′ shown in FIG. 2 up to where it approaches R. Thus, it was found while the size and number of steps or protrusions **52** and **54** may vary, it is necessary to locate them in the center of the pole faces, to make them symmetrical across the face, and have the faces parallel to that of the pole faces. An incidental but important advantage resulting from this invention is that it makes it possible to accommodate for a given magnetic field, coil assemblies using bigger copper conductors with the result that losses can be reduced and greater magnet efficiency is obtained without sacrificing field linearity.

It is thus seen that there has been provided a unique and remarkably effective approach to the problem of eliminating unwanted distortions in the field of a quadrupole magnet. While only a preferred embodiment has been shown it is understood that many changes thereof may be made without departing from the principles of this invention which is limited only by the scope of the appended claims.

We claim:

1. A quadrupole electro-magnet comprising:

(a) four pole pieces assembled in spaced relationship to form the corners of a rectangle and a central air gap, each of said pole pieces having a flat pole face bordering said air gap;

(b) coils wrapped around each of said pole pieces to carry electric current to establish magnetic fields and fluxes in said pole pieces; and

(c) means consisting of protrusions mounted integrally on each of said pole faces to minimize distortion in the magnetic field extending through said air gap, said protrusions on each pole face being stepped and having surfaces facing said air gap parallel to the flat surface of the respective pole face.

2. The magnet of claim **1** in which the protrusions in each pole face extend the whole length of the latter and are symmetrical across the width of the pole face.

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