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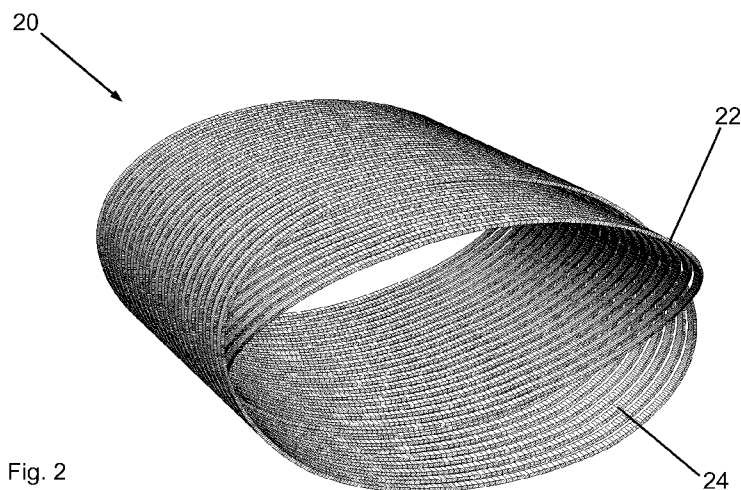


Fig. 2

(57) Abstract: A magnet (20) for a particle accelerator comprises at least first and second concentric tubular coils (22, 24), with each of the coils comprising a plurality of turns. The coils (22, 24) are arranged to provide at least two regions of constant current density in a direction parallel to the axis of the magnet in opposite respective directions.

## Magnets

5           This invention relates to magnets for bending and focussing moving charged particles, particularly in particle accelerators.

Particle accelerators have widespread uses in scientific research as probing instruments to investigate the structure of matter, e.g. high energy particle physics, X-ray and neutron scattering, and for a diverse range of industrial applications, e.g.  
10   ion implanters for semiconductors, surface hardening, synchrotron radiation sources, and medical applications (radiotherapy, biomedical research and radioisotope production).

Conventionally, charged particles are accelerated in circular accelerators where the particles are kept in the accelerator for multiple revolutions. To keep the  
15   particles within the beam pipe of the accelerator, bending magnets are needed to make the particles follow a curved trajectory. Conveniently such accelerators have a circular particle trajectory, but this is not essential and other loop shapes are possible.

The Lorentz force,  $F=q(E + \mathbf{v} \times \mathbf{B})$ , describes the force experienced by a  
20   charged particle with velocity  $\mathbf{v}$  and charge  $q$  in an electric field  $\mathbf{E}$  and magnetic field  $\mathbf{B}$ . Considering when only a magnetic field is present, the force experienced by the particle is perpendicular to both the magnetic field and the component of its velocity perpendicular to the magnetic field. Therefore if the velocity of the particle is only in this direction, i.e. perpendicular to the magnetic field, the trajectory of the particle  
25   will be a circle if the magnetic field is homogeneous.

Therefore if a homogeneous magnetic field is created across the area of a circular particle accelerator, perpendicular to the plane of the accelerator and a supply of particles is injected into the magnet, they will circulate within the accelerator as long as the magnetic field is chosen correctly. A magnet able to  
30   perform this function is called a dipole magnet which has a homogeneous magnetic field over a certain region and bends particles in a circular path.

Conventional magnets use a solid iron core around which a coil is wound to create the desired field, the core amplifying the magnetic field created by the coil. The maximum field obtainable with such a magnet is approximately 2 T, at which

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point the iron core saturates and only an insignificant increase in magnetic field is possible as the current in the coil is increased.

The magnetic rigidity of a charged particle describes the relationship between the radius of curvature in a magnetic field with the particles' momentum, which can be derived from balancing the Lorentz force with the centrifugal force to give  $B\rho = p/q$  where  $B$  is the magnetic field,  $\rho$  is the radius of curvature,  $p$  is the particle's momentum and  $q$  is the particle's charge. For a given application, particles of a certain energy, and therefore momentum, are generally required. For example in radiotherapy using protons, an energy of 250 MeV is required, e.g. to treat tumours at a maximum depth of 25 cm below the skin. This means that once the energy has been set, the magnetic field and radius are inversely proportional to each other, and therefore if an accelerator with a small radius is required, e.g. to fit into a confined hospital space, a large magnetic field is required.

The solution to providing a magnet which can create a magnetic field greater than 2T is to dispense with the iron core and to use electromagnets. In this respect superconducting magnets are very attractive as they require relatively little power, owing to the fact that the electrical resistivity is zero. Superconducting magnets routinely produce magnetic fields in excess of 22 T.

Conventional superconducting electromagnets for particle accelerators, which generally have a circular bore, are constructed by arranging a number of coil segments around the coil bore, each of which carries a constant current, with the current running along the axis (z-direction) of the magnet. The net current is varied around the circumference of the bore to give the required distribution, e.g. for a dipole magnet this is a cosine theta distribution, i.e.  $J_z \propto \cos(\theta)$ , where  $J_z$  is the z-component of the current and  $\theta$  is the azimuth angle, which results in the creation of a dipole magnetic field across the interior of the bore.

It is also known that a dipole field can be generated in theory by creating two areas of constant current density, the shapes of which correspond to the shapes formed by the non-overlapping portions of two identical but laterally offset ellipses. In practice the field can be approximated by the use of two sets of coil segments carrying the same constant current, with the current running along the axis (z-direction) of the magnet in opposite directions. However the finite size of, and need to provide return paths for, each individual coil segment means that there is a limit to how accurate an approximation can be achieved, especially for relatively smaller magnets.

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Another important concern for particle accelerator magnets is the required beam aperture, which needs to be large enough to accommodate the beam. The beam aperture is determined by the optical lattice of the accelerator. For all magnets it is desirable to have as small an aperture as possible to minimise the cost, and for some accelerators this is a particular challenge, e.g. fixed field alternating gradient (FFAG) accelerators, as the aperture is required to be relatively large to accommodate the large radial excursions of the particles in such accelerators. The Applicant has appreciated that when using a magnet design with a circular aperture this is wasteful since the excursions are mainly confined to one transverse axis and thus a large proportion of the circular aperture is not usefully employed.

Furthermore, in order to create a high quality magnetic field over the entire length of the magnet, the effects of the ends of the coil, which return the current, need to be considered. This is particularly important when a magnet has a large aperture and a short length, giving it a small aspect ratio (ratio of length to radius of aperture). Conventional coil ends make little useful contribution to the magnetic field as they are simply artificial structures which need to be employed to return the current back into the main body of the coil, and thus they reduce the available space for the 'useful' part of the magnet. A further disadvantage of the coil ends is that they introduce field errors.

The present inventors have appreciated that there are shortcomings with conventional electromagnets and the present invention aims to address these.

From a first aspect the invention provides a magnet for a particle accelerator comprising at least first and second concentric tubular coils, each of said coils comprising a plurality of turns, wherein the coils are arranged to provide at least two regions of constant current density in a direction parallel to the axis of the magnet in opposite respective directions.

The Applicant has appreciated that by arranging two concentric tubular coils in this way, a high quality magnetic field can be provided since they give continuous regions of constant current density, thereby avoiding the inevitable discontinuities arising when trying to approximate regions of constant current density with separate coil segments as in conventional electromagnets. Furthermore, the arrangement of the coils in accordance with the invention obviates the need for additional, artificial structures at the ends of the coils, as are needed in conventional electromagnets to return the current but which add unwanted components to the magnetic field. The

continuous tubular coils can therefore closely reproduce the constant current density regions which produce the required fields, e.g. a pure multipole field.

Yet another benefit is that the integral field quality of these concentric coils is very good, as field errors (unwanted harmonics) tend to cancel out. The present invention therefore offers a significant improvement over conventional magnets in  
5 mitigating field errors. The whole length of the coils of the present invention can contribute usefully to the desired magnetic field.

In one set of embodiments the common axis of the coils is a straight line. The transverse cross-sectional shape of the coils may take a number of different  
10 forms, e.g. a circle but in one set of preferred embodiments the cross-sectional shape of each coil is an ellipse. In another set of embodiments the axis of the coils is curved. Again the cross section may also take a number of different forms, e.g. a circle, but again preferably an ellipse. In some of these embodiments therefore the magnet could be part of a torus. As explained previously a dipole magnet deflects  
15 a charged particle travelling through the magnetic field, so sometimes coils in the form of a curved tubes will be advantageous. However when using curved tube coils it is more difficult to produce pure multipole fields, e.g. a when trying to create a dipole, the magnet would often include a small component of a quadrupole. These higher order field components can be compensated by adding a separate  
20 multipole coil to create a combined function magnet or by hardwiring extra multipoles into the coil as will be described later.

As used herein the term 'axis' of a coil should be taken to be a line through the centre of the coil parallel to the sides of the coil.

The present invention is particularly suitable for providing coils with elliptical  
25 cross-sections, and such magnets afford a number of advantages. For a magnet based on the  $\cos(\theta)$  principle as discussed above, it is not possible to arrange the current around the circumference of an elliptical bore such that a pure multipole magnet is generated. However for a magnet based on the constant current density principle of the present invention, a number of different shapes are possible,  
30 particularly ellipses. This stems from the general principle, as previously discussed, that a dipole and quadrupole magnetic fields can be generated by arranging intersecting ellipses of constant current density. As for these multipoles the coils need to be arranged to give these regions of constant current density, the most natural choice for the cross-sectional shape is therefore an ellipse.

Having a non-circular, and particularly an elliptical, cross-section for the coils can be particularly advantageous for some particle accelerators. This is because the beam aperture, and therefore beam pipe, can be non-circular, e.g. in FFAGs, primarily because the particles are in a circular orbit, so the spread of particles is greatest in the transverse rather than vertical direction, for which an elliptical aperture is therefore most suitable to match the shape of the spread of particles within the beam. For example, for a particle accelerator with a radius of 6 m, bending protons of energy 250 MeV, the beam aperture is 160 mm x 25 mm. Therefore if a round bore coil was to be used, approximately only 20% of the magnet bore would actually ever be used for the particles. This is a huge waste of magnetic energy as the circular coils are providing a magnetic field in a large volume where it is not needed. Instead, an elliptical aperture is far more suitable as the coils can then match the shape of the particle beam and thereby waste less space. In this arrangement the required magnetic field is only generated in the volume in which it is needed, and therefore results in a more efficient magnet as less magnetic energy is necessary compared to that generated by an equivalent magnet with a circular bore able to accommodate the same beam. As the overall magnetic energy required is reduced, this leads to a cheaper cost for a given field strength, i.e. the magnet is more efficient in this configuration.

Yet another advantage in providing an elliptical coil is that it reduces the size of the magnet in the vertical direction which can aid the extraction of particles from the beam. In many particle accelerators the particles are accelerated to a certain energy and then extracted for use elsewhere, e.g. in the many applications described previously. One common method of extracting particles from an accelerator is to use a so-called "kicker" magnet, placed between the other magnets in the accelerator. A kicker magnet is energised as a beam of particles is passing through to "kick" particles from the beam out of the accelerator in a certain direction, generally the smallest dimension to clear the following magnet which is typically horizontally. It will therefore be appreciated that if the magnets are reduced in one dimension owing to having elliptical coils, the kicker magnet will not have to exert as great a force on the particles to deflect them clear of the next magnet in the accelerator in order to extract them.

A further advantageous consequence of providing an elliptical coil compared with a circular coil is that it reduces the surface area of the coils that is needed to be cryogenically cooled during operation. If the coil is cooled using cryocoolers, fewer

coolers can be used. This again reduces the energy and the volume of cooling material needed, and therefore the cost of running the magnet.

Preferably the regions of constant current density comprise at least one region in which the constant current density is provided in the opposite direction to the constant current density in at least one other region. Where two regions of  
5 constant current density are provided, preferably the current density in the two regions has the same magnitude over an equal area. In general, to help achieve this, current is sent in one direction through the first coil and the opposite direction through the second coil, i.e. the current through the first and second coils is  
10 arranged to flow in opposite directions through the magnet. However locally, the direction of the current density is achieved by the direction of the turns in the coils, particularly in the axial direction.

Preferably the coils are arranged to produce a magnetic field in which the solenoid components of the magnetic field generated by the coils are at least  
15 partially mutually cancelled. Arranging the coils partially to cancel their solenoid fields enables a high quality magnetic field, e.g. a multipole field to be provided. The arrangement of the present invention is particularly suited to providing such cancellation of the solenoid field. One reason for this is that if currents are passed through each of the coils in different directions and the turns of the coils are suitably  
20 arranged, i.e. such that the currents in the transverse directions cancel and add in the axial direction, the effect is that the solenoid (axial) fields cancel, and the multipole fields add (e.g. for a dipole this field is perpendicular to the axis), giving a high quality multipole field. The multipole field generated by the two (or more) coils of the present invention can have smaller errors than a conventional multipole  
25 magnet with coil segments because it is a better approximation to a constant current density distribution.

In one set of embodiments the regions of constant current density are arranged to provide a multipole magnetic field, or a superposition of multipoles. For example, as has already been discussed, if constant current densities of equal  
30 magnitude are provided in opposite directions parallel with the axis of the magnet in the two parts of intersecting virtual ellipses which do not overlap, e.g. a current density of  $+J$  in the first region and  $-J$  in the second region, a dipole field is generated. By virtual ellipses, this is meant to distinguish these ellipses which are merely used for design purposes to map out the desired current density distribution,

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which is then implemented by the physical coils of the magnet, which can themselves have an elliptical cross-section.

Different arrangements of regions of constant current densities can be provided to generate different types, i.e. orders, of multipoles or different  
 5 superpositions of multipoles. For example, if two ellipses with different eccentricities are intersected about their common centre, four regions are created which define the non-overlapping areas. If, in these regions, alternately directed constant current densities are provided, e.g. +J in the first region, -J in the second region, +J in the third region and -J in the fourth region, where the first and third  
 10 regions are spatially opposite each other, and the second and fourth regions are spatially opposite each other, a quadrupole field is generated.

In one set of embodiments the following general equation can be used to generate geometries for the regions of constant current density which result in multipole fields:

$$\begin{aligned} 15 \quad x &= a \cos(\Theta) - c \sin(n\Theta + \phi_0) \\ y &= b \sin(\Theta) - c \cos(n\Theta + \phi_0) \end{aligned}$$

In this equation  $\Theta$  is a parameter which is varied from 0 to  $2\pi$  (n.b. this is not the azimuthal angle). The parameters a and b are the equivalent of the half axis of an ellipse, c is an additional parameter which for an ellipse influences its shape,  $\phi_0$  is  
 20 the phase angle ( $\pi/2$  for a normal multipole), and n is the multipole order, e.g. n=1 for a dipole, n=2 for a quadrupole, n=3 for a sextupole, etc.

This equation generates the first shape, with the second intersecting shape obtained by replacing c with -c. In general, as has been discussed for particular examples, the non-intersecting areas of the overall geometry need to be filled with a  
 25 constant current density. Furthermore, in general, the direction of the current density in the non-intersecting areas is alternating so that an area of positive current density is not next to an another area of positive current density.

Although this equation can be used to easily generate the required shapes for the regions of constant current density, in general, any distribution of regions of  
 30 constant current density, which generates the required magnetic field, can be used. This is particularly the case for a superposition of multipole fields when the shapes need to be chosen to give the required proportions of the different multipole fields making up the superposition. One way to do this for a superposition is to simply superpose the distributions for the individual multipoles.

Once the distributions of the current densities have been produced to give the desired magnetic field, the arrangement of the paths of the turns of the coils have to be derived from these.

First, the coil geometry in two dimensions has to be determined, i.e. the cross-sectional shape of the coil. The geometry of this cross-sectional shape, a path in 2D, is chosen so that it overlaps with the "ideal" geometry of the current density distributions which have already been generated. The path of the wire can be any desired shape which best passes through all the current density regions, but in some sets of embodiments it is elliptical or circular, e.g. to match with the intersecting ellipses in some embodiments. To determine the position of the wire in the longitudinal (z) direction, i.e. parallel to the axis of the coil, a number of points on this 2D path are chosen, in general so that for each point the azimuthal angle increases by an equal amount between successive points. Each point can be associated with a small change in z (dz), depending on if the point is in an area of positive or negative current density distribution (or zero if in neither), e.g. if the point is in an area of positive current density the change in z is positive and vice versa. For example, the longitudinal position  $z_1$  of the wire at a point  $s_1$  on the path  $s$  of

the turns can be calculated from the following integral: 
$$\int_0^{s_1} g(s) ds = z_1$$

where  $g(s)$  is a function with the corresponding values of -dz, +dz or 0 along the path  $s$ .

Preferably the path of the turns of the coil is chosen so that geometric path integral of a turn of wire around the coil is less than or equal to three times the thickness of the wire, e.g. less than or equal to two times, e.g. equal to the thickness of the wire. As will be appreciated this is achieved by having adjacent turns of the coil as close to each other as possible.

This procedure generates a single turn of a coil, with further turns being generated by stepping the subsequent turn by a winding pitch distance,  $p$ , in  $z$ . This winding pitch is generally added as a constant function of the azimuthal angle, e.g.  $z = p\theta/2\pi$ . In general, the second coil can be generated by reversing the path in  $dz$ , with the radius (or equivalent dimension if an ellipse or other shape is provided) of the second coil having to increase to allow for the radial thickness of the wire of the turns.

It will be appreciated that if the path of the second coil is the reversal of the path of the first coil in  $z$ , and the current is passed through the coils in opposite directions, the transverse components of the magnetic field, which contribute to the useful multipole magnetic field, will add and the solenoidal (axial) components will tend to cancel.

Therefore in one set of embodiments, the paths of the turns are arranged such that for the first coil  $z = p(\theta) + f(\theta)$ , where  $z$  is the coordinate along the axis of the coils,  $\theta$  is the azimuthal angle,  $p(\theta)$  is a term representing the winding pitch of the turns, and  $f(\theta)$  is a term chosen to provide the required current density distribution, and for the second coil  $z = p(\theta) - f(\theta)$ . In one set of embodiments  $f(\theta)$  may vary along the length of the coils, but in the set of embodiments in which  $f(\theta)$  is constant for the length of the coils, the second coil can be thought of as the mirror image of the first coil about a plane through the middle of the coils perpendicular to the axis of the magnet (ignoring the generally negligible term of the winding pitch). In general  $p(\theta)$  is constant along the length of the coils.

In general,  $f(\theta)$  will not be a simple mathematical formula, such as  $\sin(\theta)$ , but instead will comprise sections of paths fitted together to give the required current density distribution. Preferably the paths of the coils comprise sections in which the gradient of the path is constant, e.g. the section can be described by the formula  $z=as$ , giving a constant derivative  $dz/ds=a$ . This therefore generates a constant current density which, when two concentric coils are provided, one with sections described by  $z=ay$  and the other with sections described by  $z=-as$ , the longitudinal components of the current density add to give the required constant current distribution and therefore the desired transverse magnetic field, and the azimuthal components of the current density cancel to give cancellation of the solenoid field.

In a preferred set of embodiments, the spacing between the turns of each coil is constant for all values of the azimuthal angle and/or along the length of the coils (it is to be noted that the winding pitch previously referred to, is a related, but different quantity to the spacing between the turns). Having a constant spacing between adjacent turns of the coil is one of the ways in which a constant current density can be provided, e.g. in combination with or alternatively to providing sections of constant gradient. In the set of embodiments in which the turns of the coils comprise sections of constant gradient and the spacing is constant, it can be seen that by passing a current through these coils, the multiple turns of the coil all

at the same gradient in a given section will add to give a region of constant current density.

Providing coils with constant turn spacing (around and/or along the coils) brings a number of further advantages. First, it greatly simplifies the manufacturing as the adjacent turns of the coil can simply be wound next to, i.e. abutting, the previous turn. This removes the need for an expensive former (i.e. a support on which the coil is wound) to be used for each coil layer which is specifically customised, e.g. with grooves, to correctly position the turns of the coils so that they follow the correct path, e.g. for coils which do not have constant spacing of adjacent turns. In accordance with the invention just a simple support can be used. In exemplary embodiments the support is as thin as possible whilst retaining sufficient strength to support any pre-stress applied during winding as well as supporting the coil during operation from the Lorentz forces generated when current is passed through the coil.

In one set of embodiments only one support is used, i.e. for the inner coil winding with the outer windings being wrapped around the inner coil. Being able to wind adjacent turns next to each other and dispense with a former for each separate coil allows the magnet, in one set of embodiments, to be manufactured simply by wrapping the coils around a base structure, e.g. a support, a former or a beam pipe, where they may be fixed in place using a resin. Further coils can then be added by winding them around the existing coils and again pressing them into a resin to fix them in place, without needing to provide an intermediate former. This brings a further benefit of increasing the packing factor of the wires making up the coils, i.e. the density of the wires in the magnet, which increases the intensity of the magnetic field generated. This is because the coils can be closer together because there are no intermediate supports which tend to lead to wasted volume, which is having to be magnetised by the coils, but which is not being usefully used by particles that the magnetic field is acting on, i.e. in the bore of the magnet.

The inventors have realised that although the two coil magnet of the present invention offers a significant improvement over a conventional coil in mitigating field errors and the space issue, there is still a residual component of the solenoid field along the axis of the coil which cannot be eliminated. This, they have realised, arises because the two coils which comprise the magnet have slightly different radii owing to them being concentric. Therefore in one set of embodiments the magnet comprises third and fourth concentric tubular coils. Preferably the four coils are

arranged to produce a magnetic field in which there is substantially no solenoid component of the magnetic field. In a preferred set of embodiments the coils of the four coil magnet are arranged such that apart from their respective radii, the path of the first coil is the same as the path of the fourth coil, and wherein, apart from their  
5 respective radii, the paths of the second and third coils are the same as each other. In this embodiment the first coil is the innermost coil, i.e. the one with the smallest radius, the fourth coil is the outermost coil, i.e. the one with the largest radius, and the second and third coils are the middle coils between the first and fourth coils. Except where otherwise discussed, the present invention is not limited to a  
10 particular shape of coil. The use of the word radius thus does not imply that the coils have a circular cross section but rather it is just an indication of the relative size of the coils.

Providing four coils in oppositely-wound pairs, with the inner and outer coils having the same path (at slightly different radii of course) and the intermediate two  
15 coils following the same path (again apart from the different radii of the coils), has been found to reduce the problem of the non-cancelling solenoid field in the two-coil magnet significantly since when an equal current is sent through the coils (in one direction for the inner and outer coils and the opposite direction for the two middle coils). In this set of embodiments with four coils, the solenoid field substantially  
20 cancels leaving a multipole field remaining. This design of magnet coil is therefore particularly suitable for use when a magnet with a short length and/or large aperture is required, because the cancellation of the solenoid field helps to reduce the field errors significantly at the ends of the magnet, although many other applications are possible.

25 Although this set of embodiments is defined in terms of two intermediate coils, i.e. the second and the third coils, it should be understood that because these follow the same path, they can be thought of as a single coil with a double layer of turns or a single layer with turns of twice the radial thickness.

As well as improving the cancellation of the solenoid field, providing four  
30 coils in accordance with this set of embodiments gives the additional benefit of providing further points within the regions of constant current density enabling the desired current density distribution to be approximated better. For this purpose, a further set of embodiments is envisaged in which these additional coils do not necessarily have to be provided in the order set out for the previous set of  
35 embodiments, i.e. the first coil being the innermost, the fourth coil being the

outermost, etc. In this set of embodiments the first coil and/or the second coil each comprises one or more additional coils provided adjacent thereto. These sets of coils do not necessarily have to follow the same path but are arranged to provide the desired current density distribution. Again, these multiple coils can be thought  
5 of as a single coil with multiple layers of turns, or a single layer with turns of multiple times the radial thickness.

Although the invention has thus far been described in terms of two or four coils this should not be considered as limiting the claims to requiring only two or four coils; additional coils could be added, e.g. to provide regions with a more  
10 uniform constant current density, to provide improved cancellation of the solenoid field, to increase the magnetic field, to provide additional multipoles, or for some other reason. Preferably however, if additional coils are provided, these are provided concentrically in groups of two or four, i.e. a magnet with more than two coils would preferably have four, six, eight or ten coils, and a magnet with more  
15 than four coils would preferably have eight, twelve or sixteen coils, etc. In the set of embodiments in which groups of four coils are provided, preferably these groups of four coils are each arranged in the same manner as the first-recited group, e.g. with the inner and the outer coils of each group following a first path and the middle coils following a second path, or in whichever arrangement is provided in the first group.

20 Preferably the number of turns is the same for all the coils. Preferably the winding pitch has the same value for all the coils. Preferably the spacing between adjacent turns is the same for all the coils. Preferably the coils are configured so that the current passing through all the coils has the same absolute value. Preferably the coils are configured so that current passes through the first coil in the  
25 opposite direction to the current passing through the second coil. Where third and fourth coils are provided, preferably the coils are configured so that current passes through the third coil in the same direction as the current passing through the second coil, and the current passes through the fourth coil in the same direction as the current passing through the first coil. These features help to ensure that the  
30 magnet in accordance with the invention generates a magnetic field for which as uniform as possible regions of constant current density are created, and the solenoid field component is reduced as much as possible.

Although the invention has been described primarily with reference to dipole magnets, this is not limiting and the invention can be applied equally to higher order  
35 multipole magnets. In other words, the path taken by the turns of the magnet coils

can be arranged to give more than two regions of constant current density.

Generally, two regions of constant current density are needed to provide a dipole magnet, four regions are needed for a quadrupole, six for a sextupole, etc. In general the different regions do not have to contain the same magnitude of the current density, e.g.  $+J$  or  $-J$ , but just current densities with alternating signs that have the boundary condition of the path integral being zero across all the regions of constant current density.

Higher order multipole magnets such as quadrupole and sextupole magnets are typically used in particle accelerators because the case of an ideal charged particle circulating in a dipole field does not exist. There are many systematic errors that result in the defocusing of the particle beam: radiation losses in the dipole magnets, gravity, field imperfections, ground motion, alignment of the accelerator, having a limited physical aperture, errors in the power supplies and calibrations, which all result in errors in the magnet strength, and variations in the energy of the particles. As a result of these factors, if purely dipole magnets were employed, particles in the accelerator would tend to spread out transversely and longitudinally and eventually get lost from the accelerator. Other magnets are therefore used to compensate for the spread in particles and so reduce the loss of particles from the beam pipe.

Quadrupole magnets produce a magnetic field which is able to correct for the transverse spreading of the particle beam by focusing the particles back towards the axis of the accelerator beam pipe. In practice, a lattice of quadrupole magnets is provided which alternately focuses and defocuses the particles in order to keep them centred within the beam pipe.

Sextupole magnets produce a magnetic field which is able to correct for the longitudinal spreading of the particle beam. Different particles within the beam will have different energies and therefore they are bent a different amount by the dipole magnets. This is comparable to chromatic aberration in optical lenses where different frequencies of light experience a slightly different refractive index and therefore are focused to a slightly different point, resulting in spreading of the image. Sextupole magnets are able to correct for this by deflecting particles with a higher energy an extra amount in order to keep the beam of particles collimated.

Sometimes it is necessary to include even higher order multipoles, e.g. octupole (generally having eight regions of constant current density), decapole (generally having ten regions of constant current density) magnets and further

higher order multipoles still, in particle accelerators to keep the beam of particles within the beam aperture.

The turns of the coils are preferably arranged to provide a multipole magnet or a superposition of multipole magnets, as has been discussed previously, by  
5 arranging the coils to give the required current density distribution. In some accelerator designs the magnetic field required from a single magnet is a mixture of the fields produced from different multipoles, e.g. mostly a dipole field with a smaller component of a quadrupole field. Such a type of magnet is known as a combined function magnet. This can be achieved in accordance with the present invention,  
10 again by arranging the turns of the coils to give the appropriate regions of constant current density for that multipole superposition, as has been discussed previously. The superposition of the different multipole components could be a non-linear superposition, e.g. when using iron in the magnet design for shielding purposes, but in a preferred set of embodiments the superposition is a linear superposition.

15 However for the type of combined function coil discussed above the ratio of the multipole fields is hardwired into the coil thus eliminating one degree of freedom. In an alternative set of embodiments, when a combined function magnet is required, a plurality of different discrete multipole magnets concentric to each other can be provided. For example, this type of combined function magnet could  
20 have two or four coils creating a dipole field which could be concentric with a higher order multiple comprising two or four additional coils. The magnetic field produced in such embodiments is a superposition of the fields created by each multipole, thus allowing the different multipole terms to be achieved, but with a separate set of coils for each different discrete multipole. The path of the turns for each of these  
25 multipoles and the current passing through them can be chosen to give the desired ratio between the strength of the different multipoles which are included in the magnet. As each of the multipoles is effectively a separate magnet, the current passing through the coils can be fine-tuned individually to give the desired balance between the different multipoles once the magnet is in operation which is not  
30 possible with a "hardwired" combined function magnet, and therefore such an arrangement gives greater flexibility in this regard.

The different multipole magnets can be arranged in arbitrary order, but usually it is preferred to position the multipole which produces the highest magnetic field as the innermost magnet. This helps to minimize the air volume the particular  
35 magnet has to magnetise.

As has been explained previously, different multipole magnets are used in a particle accelerator to keep the beam of particles within the accelerator. There may be a further requirement that the magnets are arranged for focusing and defocusing. Focusing and defocusing magnets are typically arranged in a lattice along the beam line of a particle accelerator, alternating between focusing and defocusing magnets. The alternate focusing and defocusing magnets converge and diverge the beam of particles in the accelerator respectively and, like an array of optical lenses, help to collimate the beam of particles in the accelerator and confine the particles within the aperture of the magnets. Without both focusing and defocusing magnets present, the particle beam would quickly be lost from the accelerator.

Focusing and defocusing magnets have different magnetic polarities, so either the coils are rotated through  $180/n$  degrees with respect to the accelerator beam line, where  $n$  is the multipole order, or the current direction is reversed to change from one type of magnet to the other. In practice focusing and defocusing magnets may differ in their magnetic field strength, depending on the design of the lattice of the accelerator in order to provide the necessary forces on the particle beam. Therefore the magnet parameters, e.g. distribution of regions of constant current density, number of turns, winding pitch, spacing between adjacent turns, etc. may differ between focusing and defocusing magnets, or it may be possible to use the same magnet design for both types of magnets but with different currents. As multipole magnets focus in one plane and defocus in the other, the magnets in accordance with the present invention are suitable for use as both focusing and defocusing magnets.

As was mentioned previously, magnets in accordance with the invention could be suitable for any particular use in particle accelerators. However, owing to their suitability in providing a high quality magnetic field in which the field errors at the ends of the magnet are reduced, the magnets of the present invention are particularly suitable for magnets with a short length and/or a large aperture, which gives them a small aspect ratio (ratio of length to radius of aperture), in which the effects of the ends of the coil, which return the current, become important.

Therefore, in one set of embodiments, e.g. suitable for accelerating protons, the coils have a length of between 30 and 80 cm, e.g. between 50 cm and 60 cm, e.g. approximately 55 cm. In another set of embodiments, e.g. suitable for accelerating carbon ions, the coil length is between 80 cm and 150 cm, e.g.

between 90 cm and 140 cm, e.g. between 100 cm and 130 cm, e.g. approximately 115 cm. Also, as mentioned previously, the present invention is equally applicable for longer magnets. Indeed the possibility of manufacturing the magnet without intermediate formers is advantageous in the context of longer magnets since it is  
5 either too expensive or practically infeasible to produce very long tubular formers

As previously explained, the radii of the coils differ from one to another. The mean radius (i.e. the radius of a circular coil, or the mean of the half axes of an elliptical coil) is in one set of embodiments however between 5 cm and 40 cm, e.g. between 10 cm and 30 cm, e.g. between 10 cm and 25 cm or 15 cm and 30 cm.

10 Thus it can be seen that the invention can be implemented by a magnet which is short with a large aperture and is therefore suitable for small radius particle accelerators, e.g. of radius approximately 6 m, where a large aperture is required to conserve a large proportion of the injected particles. However it will be appreciated that for the embodiments in which multipole magnets of different orders are nested  
15 within each other, e.g. with a dipole in the centre inside a quadrupole which is in turn inside a sextupole, etc., the radii of the coils will be different for the different multipole coils. This contrasts to the length of the coils which will be relatively similar for all the different order multipoles.

The invention can be used where the ratio of the coil length to the magnet  
20 aperture radius (the "aspect ratio") is less than 15:1. In one set of embodiments, e.g. suitable for accelerating protons, the ratio is less than 5:1, e.g. less than 4:1, and e.g. less than 3:1. This is small compared to the typical corresponding ratio for a conventional magnet. In another set of the embodiments suitable for accelerating carbon ions the coils are longer and therefore for example the coil aspect ratio is  
25 less than 8:1, e.g. less than 7:1, e.g. less than 6:1. For magnets with a small aspect ratio, the end effects of the magnetic field become very important, and thus it can be seen that the present invention gives a magnetic field which is particularly suitable for magnets with these dimensions.

30 Although the high quality nature of the magnetic fields make the magnets of the present invention suitable for short magnets, they are equally applicable for longer magnets, particularly because of the previously described manufacturing advantages. Because the individual coils making up the magnet do not need to each be supported by a former, which especially if they comprise a groove are particularly expensive, it is economically feasible to provide these types of magnets

for applications in which longer magnets are required, e.g. larger particle accelerators.

Magnets in accordance with the invention could be conventional electromagnets, superconducting or hybrid magnets. Where it is a conventional  
5 electromagnet, if cooling is required, the coils may be e.g. cooled by water. In one set of embodiments the wires are made from NbTi superconductor, though other materials such as Nb<sub>3</sub>Sn and high temperature superconductor materials are also envisaged. The copper to superconductor ratio may be as high as 20:1, but preferably the copper to superconductor ratio is between 1.2:1 and 2.1:1, preferably  
10 approximately 1.35:1. Superconducting wires allow high magnetic fields to be reached which are not possible using a conventional electromagnet.

In one set of embodiments the wire used to wind the coils is a single filament wire, e.g. a superconducting NbTi wire with 54 NbTi filaments embedded in a Cu matrix, for example a single filament rectangular wire. In another set of  
15 embodiments the wire used to wind the coils is a Rutherford cable (a multi filament wire), e.g. with 5 strands each with a diameter of about 1 mm giving outer dimension of about 3 mm × 2 mm.

In the embodiments in which superconducting wires are used, the coils can be cooled below the critical temperature of the superconductor using a bath  
20 cryostat, but many other methods known to those skilled in the art for realising the cryostat could alternatively be used. For a superconductor made of NbTi the critical temperature is approximately 9.2 K.

Preferably the plurality of turns for each coil comprises between 100 and 400 turns, preferably between 200 and 300 turns, preferably between 240 and 260  
25 turns. Providing a large number of turns for a coil helps to provide a high, uniform magnetic field. The number of turns will vary depending on a number of factors including the desired magnetic field, the type of wire used and what sort of particles the accelerator including the magnet is designed to accommodate.

Preferably a combined function magnet in accordance with the present  
30 invention is arranged to deliver a peak magnetic field between 1 T and 8 T, e.g. between 2 T and 6 T, e.g. between 4 T and 5 T, e.g. about 4.5 T. As described previously a combined function magnet is a superposition of a number of different multipoles which each have a different value for their peak magnetic field. Examples of such values for the different multipoles for a lattice of magnetic length  
35 314.4 mm, with the peak fields calculated at a radius of 0.14 m are: 1.95 T for a

dipole, 1.65 T for a quadrupole, 0.71 T for a sextupole, and 0.19 T for an octupole. The combined field of all these multipoles in such a combined function magnet varies across the horizontal direction, i.e.  $x$ , from 0.8 T to 4.5 T.

A magnet capable of delivering high strength magnetic fields set out above is suitable for inclusion in a small radius particle accelerator, e.g. of radius 6 m where a large magnetic field is needed to bend protons with an energy of approximately 250 MeV. As with many of the other dimensions and values which describe the magnet coil, the peak magnetic field differs between different multipoles and whether the magnet is being used for proton or carbon acceleration.

The magnet provided by the present invention is suitable to be used in a number of different particle accelerators, e.g. fixed field alternating gradient (FFAG) accelerators which have a number of applications, such as in hospitals for radiotherapy treatment; in scientific research for neutrino factories, muon sources and proton drivers; in industry for accelerator driven subcritical reactors (ADSR).

Certain preferred embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings in which:

Fig. 1 shows a schematic of two intersecting ellipses to create a current density distribution for a dipole magnetic field;

Fig. 2 shows an isometric view of the structure of the coil turns for a dipole magnet;

Fig. 3 shows a side view of the coils of Fig. 2;

Fig. 4 shows a plan view of the coils of Fig. 2;

Fig. 5 shows a plot of the coefficients of the multipole components at a reference radius  $r_0$  along the length of the magnet shown in Figs. 2, 3 and 4;

Fig. 6 shows a schematic of two intersecting ellipses to create a current density distribution for a quadrupole magnetic field;

Fig. 7 shows an isometric view of the structure of the coil turns for a quadrupole magnet;

Fig. 8 shows a side view of the coils of Fig. 7;

Fig. 9 shows a plan view of the coils of Fig. 7;

Fig. 10 shows a plot of the coefficients of the multipole components at a reference radius  $r_0$  along the length of the magnet shown in Figs. 7, 8 and 9; and

Fig. 11 shows a lattice of magnets forming part of a particle accelerator.

Fig. 1 shows a schematic of two intersecting ellipses 2, 4 within which are constant current densities  $+J$  and  $-J$  respectively, i.e. the left hand ellipse 2 contains

a constant current density  $+J$  in a direction out of the page, and the right hand ellipse 4 contains a constant current density  $-J$  in a direction into the page. The effect of these intersecting current densities is that in a central region 6 where the two ellipses 2, 4 overlap, the two current densities in the opposite direction, which  
5 have the same magnitude, cancel. The current density in this nearly ellipse shaped central region 6 is therefore zero. In the two outer regions 8, 10 where the ellipses 2, 4 do not overlap, the resultant current density is clearly  $+J$  in the left hand region 8 and  $-J$  in the right hand region 10. These two regions 8, 10 of constant current density in the non-overlapping areas of the intersecting ellipses 2, 4 act to generate  
10 a uniform magnetic field 12 in the vertical direction, i.e. a dipole field.

Embodiments of the present invention uses concentric coils to provide these regions of constant current density in order to generate multipole magnetic fields, as will now be explained.

Figs. 2, 3 and 4 show isometric, side and plan views respectively of a dipole  
15 magnet 20 formed from two concentric coils 22, 24. In Fig. 2 it can be seen that the magnet 20 comprises an inner coil 22 arranged concentrically within an outer coil 24. Both the inner coil 22 and the outer coil 24 comprise a plurality of turns which are wound in a generally circumferential manner around the common axis of the coils. Although not shown, the inner coil 22 could be formed on a support to  
20 provide support for the windings. It is not necessary to provide an intermediate support between the inner coil 22 and the outer coil 24, the outer coil 24 can simply be wound around the inner coil 22. As the wire of the inner coil 22 is being wound round the support (if one is used), and then when the outer coil 24 is wound around the inner coil 22, a tension is applied to the wire in order to keep the wire on the  
25 correct path. After winding the coil it is usually impregnated with epoxy resin to keep the wire in place and to aid electrical insulation. Alternatively a pre-impregnated fibre cloth can be used.

The wire can either be a single filament wire such as a rectangular filament wire with a copper to superconductor ratio of 1.3:1 (obtained from Oxford  
30 Instruments Superconducting Technology, 600 Milik Street, PO Box 429, Carteret, NJ, 07008, USA), or a Rutherford cable which comprises a number of individual strands. With either the single filament wire or the Rutherford cable, the wire is usually insulated before being wound.

Each of the coils 22, 24 has an elliptical cross section, giving the magnet 20  
35 an elliptical bore. The cross sectional shape of the coils 22, 24 is chosen to pass

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through the regions of non-zero current density 8, 10 as shown in Fig. 1, as well as possible, so that the turns of the coils 22, 24 can take a path to generate the required current density distribution in these regions.

5 The paths taken by the turns of the coils 22, 24 can be better seen from the side and plan views in Figs. 3 and 4 respectively. In Fig. 3 it can be seen that the turns of the coils 22, 24 are parallel to each other in a direction perpendicular to the axis of the coils at the top and the bottom of the magnet 20. At the sides of the coils the turns are at a generally constant gradient (this being the same for both coils) to the axis of the coils, but angled in opposite directions so that the turns  
10 cross each other at a generally constant angle. Apart from its slightly different radius, the inner coil 22 is a mirror image of the outer coil 24 about a plane through the middle of the coils perpendicular to the axis of the coils.

In Fig. 4, the parallel nature of the turns of the coils 22, 24 on the top and the bottom of the magnet 20 can be seen clearly. On the top and bottom of the  
15 coils 22, 24 the turns extend parallel to each other across the majority of the width of coils.

The operation of the two coil dipole magnet shown in Figs. 2, 3 and 4 will now be described. A current  $J$  is passed through the turns of the coils 22, 24, the current being of equal magnitude for both coils. The current is passed in one  
20 direction (e.g. left to right in Figs. 3 and 4) for the inner coil 22 and in the opposite direction (right to left in Figs. 3 and 4) for the outer coil 24. In the sections of the coils at the top and the bottom where the turns are parallel to each other, the currents flow in opposite directions in the separate coils. The vector addition of these currents, i.e.  $J + (-J)$ , gives a net resultant current of zero, and therefore the  
25 current density distribution is zero in this region. Furthermore, with the turns of the coils running perpendicular to the axis of the coils, there is no component of the current flowing in the direction parallel to the axis. The zero current density in this region corresponds to the region in Fig. 1 where the ellipses intersect at the top and the bottom and where a current density of zero is desired.

30 In the sections of the coils at the sides where the turns cross each other at an angle, the vector addition of the currents in the inner coil 22 and the outer coil 24 result in the components in the direction perpendicular to the axis of the coils, i.e. the vertical or transverse direction, cancelling, and the components in the direction parallel to the axis of the coils adding. Therefore in these side regions the resultant  
35 current density distribution is in the direction parallel to the axis of the coils, and

zero in the direction perpendicular to the axis. As the current travels in the opposite direction on the opposite side of the coils, this results in the current density distributions on opposite sides of the coils being in opposite directions.

Furthermore, as the gradient of the turns in the sides of the coils is generally constant, and the spacing of adjacent turns is constant, this gives a constant current density in these regions.

As will be appreciated, a good approximation to the required regions of constant current density as set out in Fig. 1 is therefore obtained. As has previously been explained, if a current density distribution of this form is provided, a uniform dipole magnetic field within the intersecting area of the ellipses, i.e. within the bore of the magnet 20 when the coils 22, 24 are provided. With the current density being zero in all transverse directions, i.e. both at the top, bottom and sides of the coil, the residual solenoidal (axial) magnetic field is small as is desired.

Fig. 5 shows a plot of the coefficients of the multipole components of the dipole magnet as shown in Figs. 2, 3 and 4, when currents of equal magnitude are passed through the coils from opposite ends of the magnet. The vertical axis 30 denotes the value of the multipole coefficients at a reference radius  $r_0$  and the horizontal axis 32 denotes the distance along the coil. Starting from the left hand side of the coil (as viewed in Figs. 2, 3 and 4) and from the left hand side of the plot in Fig. 5, the magnitude of the dipole coefficient 34 increases rapidly to a relatively constant value. Travelling rightwards through the magnet, the dipole magnetic field 34 remains at a relatively constant value throughout the length of the magnet, and then falls back to zero in a symmetric manner when the end of the magnet is reached. Fig. 5 also shows that the magnetic field generated by the dipole magnet is almost purely composed of the dipole component. Only the sextupole component 36 can be seen to be non-zero, but its magnitude is negligible compared to that of the dipole component 34.

Fig. 6 shows a similar schematic to that shown in Fig. 1 of two intersecting ellipses 102, 104 arranged about a common centre and within which are constant current densities  $+J$  and  $-J$  respectively, i.e. the flatter ellipse 102 contains a constant current density  $+J$  in a direction out of the page, and the less eccentric ellipse 104 contains a constant current density  $-J$  in a direction into the page. Again, the effect of these intersecting current densities is that in a central region 106 where the two ellipses 102, 104 overlap, the two current densities in the opposite direction, which have the same magnitude, cancel. The current density in

this nearly ellipse shaped central region 106 is therefore zero. In the four outer regions 108, 110, 112, 114 where the ellipses 102, 104 do not overlap, the resultant current density is clearly +J in the left and right hand regions 108, 110 and -J in the top and bottom regions 112, 114. These four regions 108, 110, 112, 114 of constant current density in the non-overlapping areas of the intersecting ellipses 102, 104 act to generate a quadrupole magnetic field.

As with the case of the dipole field and magnet in Figs. 1 to 5, concentric coils are used to provide these regions of constant current density in order to generate the quadrupole field.

Figs. 7, 8 and 9 show isometric, side and plan views respectively of a quadrupole magnet 120 formed from two concentric coils 122, 124, arranged in a similar manner to the coils in the dipole magnet of Figs. 2 to 4. The distinction between the quadrupole magnet and the dipole magnet is the path that the turns of the coils takes in order to produce the different required current density distribution as illustrated in Fig. 6.

Again, each of the coils 122, 124 has an elliptical cross section, giving the magnet 120 an elliptical bore. The cross sectional shape of the coils 122, 124 is chosen to pass through the regions of non-zero current density 108, 110, 112, 114 as shown in Fig. 6, as well as possible, so that the turns of the coils 122, 124 can take a path to generate the required current density distribution in these regions.

The paths taken by the turns of the coils 122, 124 can be better seen from the side and plan views in Figs. 8 and 9 respectively. In Fig. 8 it can be seen that the turns of the coils 122, 124 are parallel to each other in a direction perpendicular to the axis of the coils at two sections on the sides of the magnet 120. In the middle of the sides of the coils, and the top and the bottom of the coils, the turns are at a generally constant gradient (this being the same for both coils) to the axis of the coils, but angled in opposite directions so that the turns cross each other at a generally constant angle. Apart from its slightly different radius, the inner coil 122 is a mirror image of the outer coil 124 about a plane through the middle of the coils perpendicular to the axis of the coils.

In Fig. 9, the constant gradient of the turns of the coils on the top and the bottom of the magnet 120 can be seen clearly. On the top and bottom of the coils 122, 124 the turns extend at this constant gradient across the majority of the width of coils.

The operation of the two coil quadrupole magnet shown in Figs. 7, 8 and 9 is very similar to the operation of the dipole magnet of Figs. 2 to 4. A current  $J$  is passed through the turns of the coils 122, 124, the current being of equal magnitude for both coils. The current is passed in one direction (e.g. left to right in Figs. 8 and 9) for the inner coil 122 and in the opposite direction (right to left in Figs. 8 and 9) for the outer coil 124. In the sections of the coils where the turns are parallel to each other, the currents flow in opposite directions in the separate coils. The vector addition of these currents, i.e.  $J + (-J)$ , gives a net resultant current of zero, and therefore the current density distribution is zero in this region.

Furthermore, with the turns of the coils running perpendicular to the axis of the coils, there is no component of the current flowing in the direction parallel to the axis. The zero current density in this region corresponds to the four points in Fig. 6 where the ellipses intersect and where a current density of zero is desired.

In the sections of the coils at the sides and on the top and bottom of the coils, where the turns cross each other at an angle, the vector addition of the currents in the inner coil 122 and the outer coil 124 result in the components in the direction perpendicular to the axis of the coils, i.e. the vertical or transverse direction, cancelling, and the components in the direction parallel to the axis of the coils adding. Therefore in these regions the resultant current density distribution is in the direction parallel to the axis of the coils, and zero in the direction perpendicular to the axis. The turns of the wire are arranged such that it results in the current density distributions in alternate sections around the coils being in opposite directions, i.e. the same on each of the sides and the same on the top and bottom, with these being opposite to each other. Furthermore, as the gradient of the turns in the sides of the coils is generally constant, and the spacing of adjacent turns is constant, this gives a constant current density in these regions. However, in this example, the gradient of the turns at the sides of the coils is greater than the gradient of the turns on the top and bottom of the coils, so the current density will have a greater magnitude at the sides.

As will be appreciated, a good approximation to the required regions of constant current density as set out in Fig. 6 is therefore obtained. As has previously been explained, if a current density distribution of this form is provided, a quadrupole magnetic field within the intersecting area of the ellipses, i.e. within the bore of the magnet 120 when the coils 122, 124 are provided. With the current

density being zero in all transverse directions, i.e. in both regions at the sides of the coil, the solenoidal (axial) magnetic field is zero as is desired.

Fig. 10 shows a plot of the coefficients of the multipole components of the dipole magnet as shown in Figs. 7, 8 and 9, when currents of equal magnitude are passed through the coils from opposite ends of the magnet. The vertical axis 130 denotes the value of the multipole coefficients at a reference radius  $r_0$  and the horizontal axis 132 denotes the distance along the coil. Starting from the left hand side of the coil (as viewed in Figs. 7, 8 and 9) and from the left hand side of the plot in Fig. 10, the magnitude of the quadrupole coefficient 134 increases rapidly to a relatively constant value. Travelling rightwards through the magnet, the quadrupole magnetic field 134 remains at a relatively constant value throughout the length of the magnet, and then falls back to zero in a symmetric manner when the end of the magnet is reached. Fig. 10 also shows that the magnetic field generated by the quadrupole magnet is almost purely composed of the quadrupole component. Only the octupole component 136 can be seen to be non-zero, but its magnitude is negligible compared to that of the quadrupole component 134.

Fig. 11 schematically shows a typical lattice of magnets arranged around the beam line 54 of a particle accelerator in accordance with the invention. The magnets are alternatively focusing 50 and defocusing 52 magnets. In operation the lattice of alternate focusing 50 and defocusing 52 magnets acts on the beam of particles passing through the lattice to converge and diverge the beam in order to keep the beam collimated within the aperture of the magnets.

It will be appreciated by those skilled in the art that many variations and modifications to the embodiments described above may be made within the scope of the invention set out herein. For example more than two coils could be employed even to produce a single magnet of given order. Also it is not essential for the oppositely-directed coils to have similar paths, their pitch and currents could be manipulated instead to give a similar result.

## Claims

1. A magnet for a particle accelerator comprising at least first and second concentric tubular coils, each of said coils comprising a plurality of turns, wherein  
5 the coils are arranged to provide at least two regions of constant current density in a direction parallel to the axis of the magnet in opposite respective directions.
2. A magnet as claimed in claim 1, wherein the common axis of the coils is a straight line.
- 10 3. A magnet as claimed in claim 1 or 2, wherein the cross-sectional shape of each coil is an ellipse.
4. A magnet as claimed in claim 1, 2 or 3, wherein the regions of constant  
15 current density comprise at least one region in which the constant current density is provided in the opposite direction to the constant current density in at least one other region.
5. A magnet as claimed in any preceding claim, wherein the current density in  
20 the two regions has the same magnitude over an equal area.
6. A magnet as claimed in any preceding claim, wherein the coils are arranged to produce a magnetic field in which the solenoid components of the magnetic field generated by the coils are at least partially mutually cancelled.
- 25 7. A magnet as claimed in any preceding claim, wherein the regions of constant current density are arranged to provide a multipole magnetic field, or a superposition of multipoles.
- 30 8. A magnet as claimed in any preceding claim, wherein the path of the turns of the coil is chosen so that geometric path integral of a turn of wire around the coil is less than or equal to three times the thickness of the wire, e.g. less than or equal to two times, e.g. equal to the thickness of the wire.

9. A magnet as claimed in any preceding claim, wherein the paths of the turns are arranged such that for the first coil  $z = p(\theta) + f(\theta)$ , where  $z$  is the coordinate along the axis of the coils,  $\theta$  is the azimuthal angle,  $p(\theta)$  is a term representing the winding pitch of the turns, and  $f(\theta)$  is a term chosen to provide the required current  
5 density distribution, and for the second coil  $z = p(\theta) - f(\theta)$ .
10. A magnet as claimed in any preceding claim, wherein the paths of the coils comprise sections in which the gradient of the path is constant.
- 10 11. A magnet as claimed in any preceding claim, wherein the spacing between the turns of each coil is constant for all values of the azimuthal angle and/or along the length of the coils.
- 15 12. A magnet as claimed in any preceding claim, comprising a support on which the turns of the coils are wound.
13. A magnet as claimed in any preceding claim, comprising third and fourth concentric tubular coils.
- 20 14. A magnet as claimed in claim 13, wherein the four coils are arranged to produce a magnetic field in which there is substantially no solenoid component of the magnetic field.
- 25 15. A magnet as claimed in claim 13 or 14, wherein the coils of the four coil magnet are arranged such that apart from their respective radii, the path of the first coil is the same as the path of the fourth coil, and wherein, apart from their respective radii, the paths of the second and third coils are the same as each other.
- 30 16. A magnet as claimed in claim 13, 14 or 15, wherein the coils are configured so that current passes through the third coil in the same direction as the current passing through the second coil, and the current passes through the fourth coil in the same direction as the current passing through the first coil.

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17. A magnet as claimed in any preceding claim, wherein the number of turns is the same for all the coils.
18. A magnet as claimed in any preceding claim, wherein the winding pitch has the same value for all the coils.
19. A magnet as claimed in any preceding claim, wherein the spacing between adjacent turns is the same for all the coils.
20. A magnet as claimed in any preceding claim, wherein the coils are configured so that the current passing through all the coils has the same absolute value.
21. A magnet as claimed in any preceding claim, wherein the coils are configured so that current passes through the first coil in the opposite direction to the current passing through the second coil.
22. A magnet as claimed in any preceding claim, wherein the plurality of turns for each coil comprises between 100 and 400 turns, preferably between 200 and 300 turns, preferably between 240 and 260 turns.
23. An accelerator comprising a magnet as claimed in any preceding claim.
24. An accelerator as claimed in claim 23 suitable for accelerating protons.
25. An accelerator as claimed in claim 23 suitable for accelerating carbon ions.
26. An accelerator as claimed in claim 23, 24 or 25 wherein the accelerator is a fixed field alternating gradient accelerator.

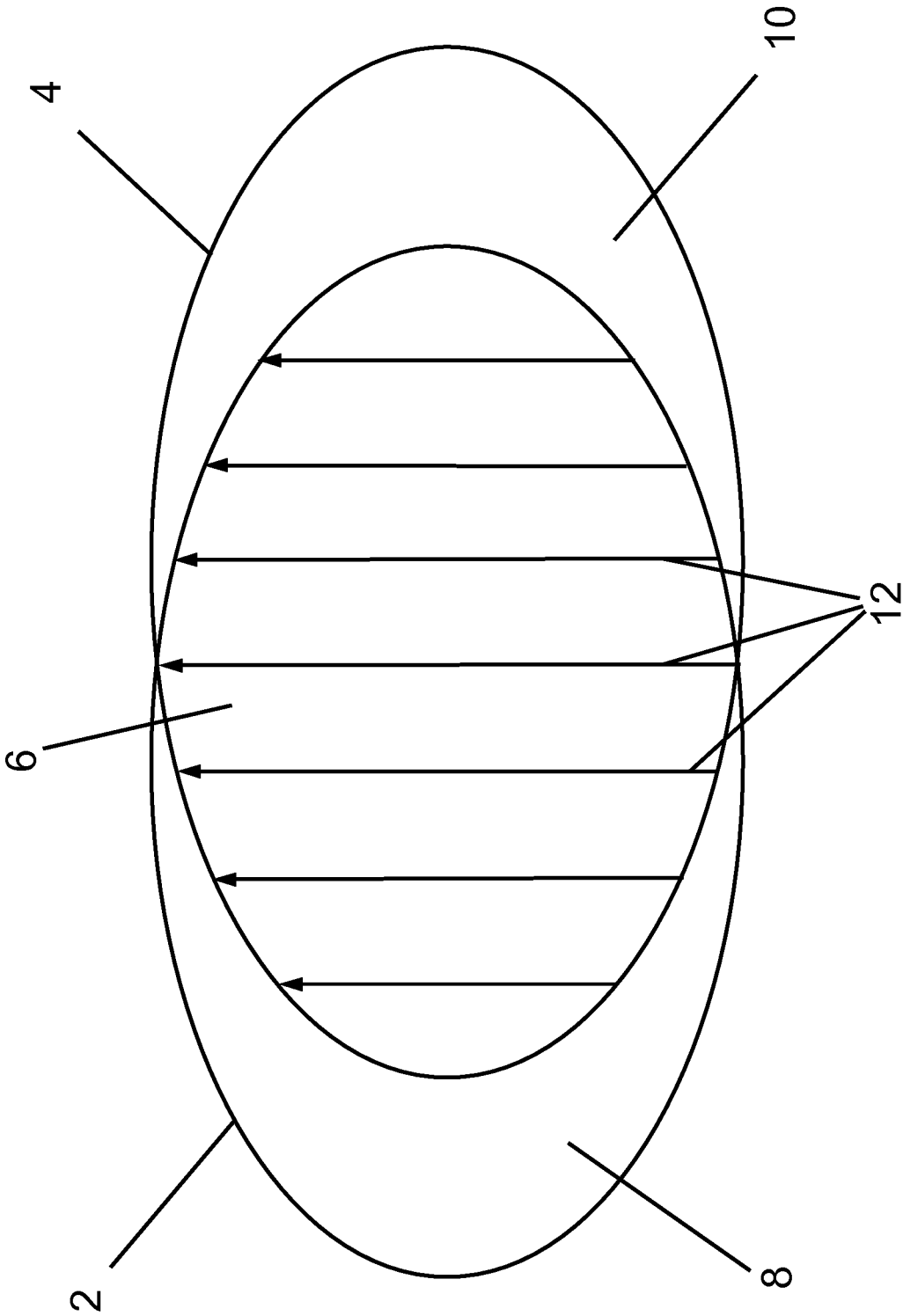


Fig. 1

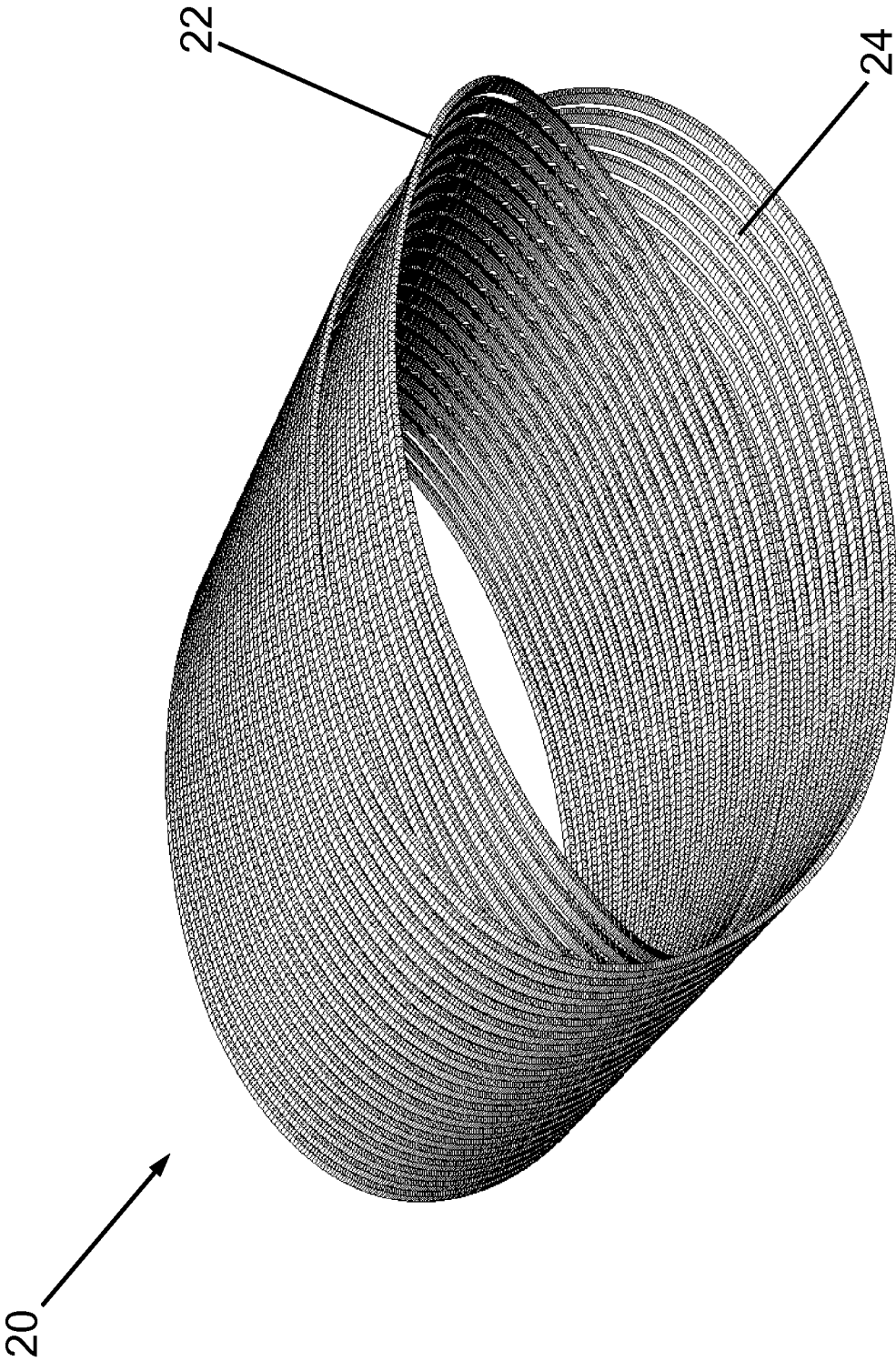


Fig. 2

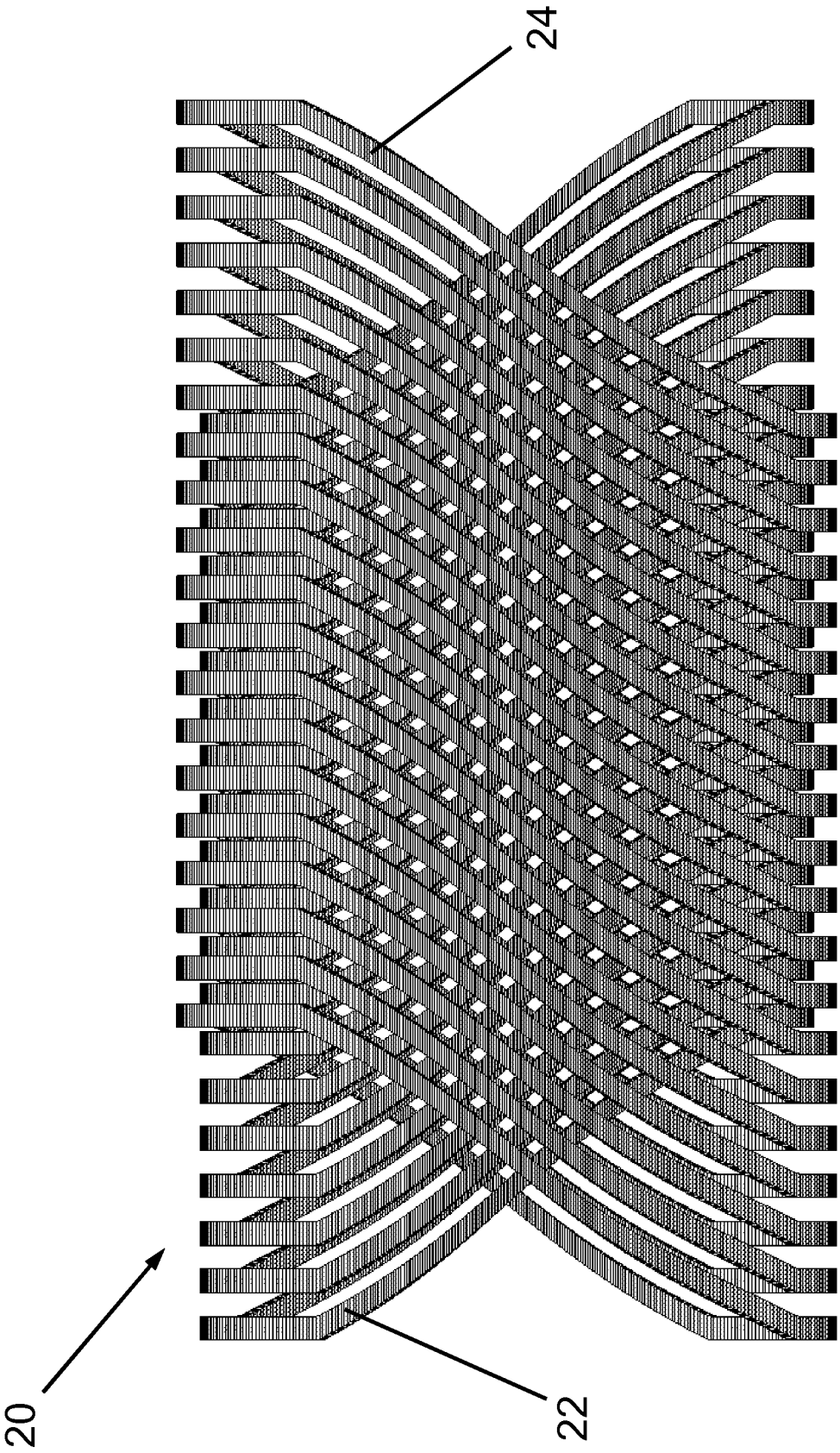


Fig. 3

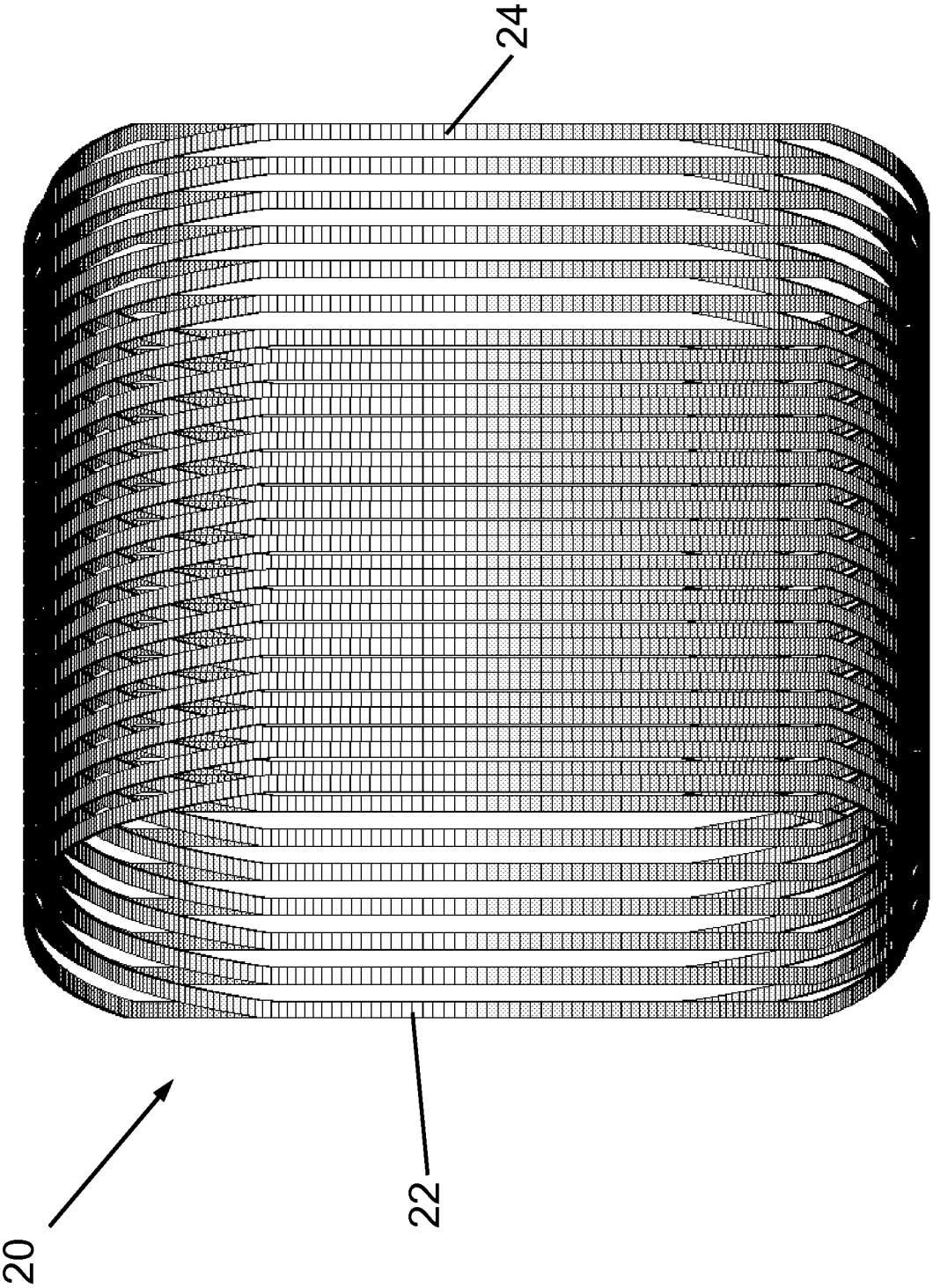


Fig. 4

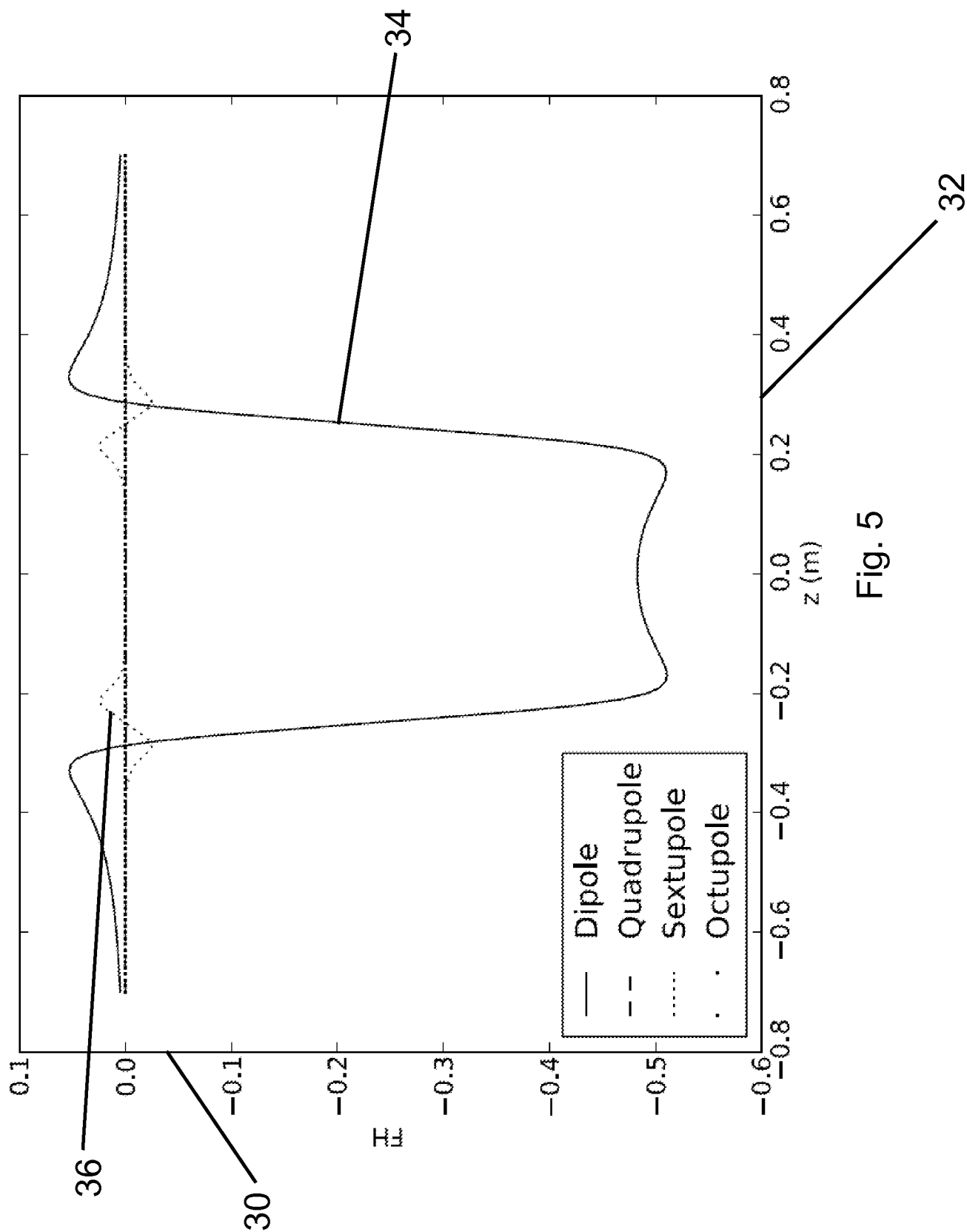
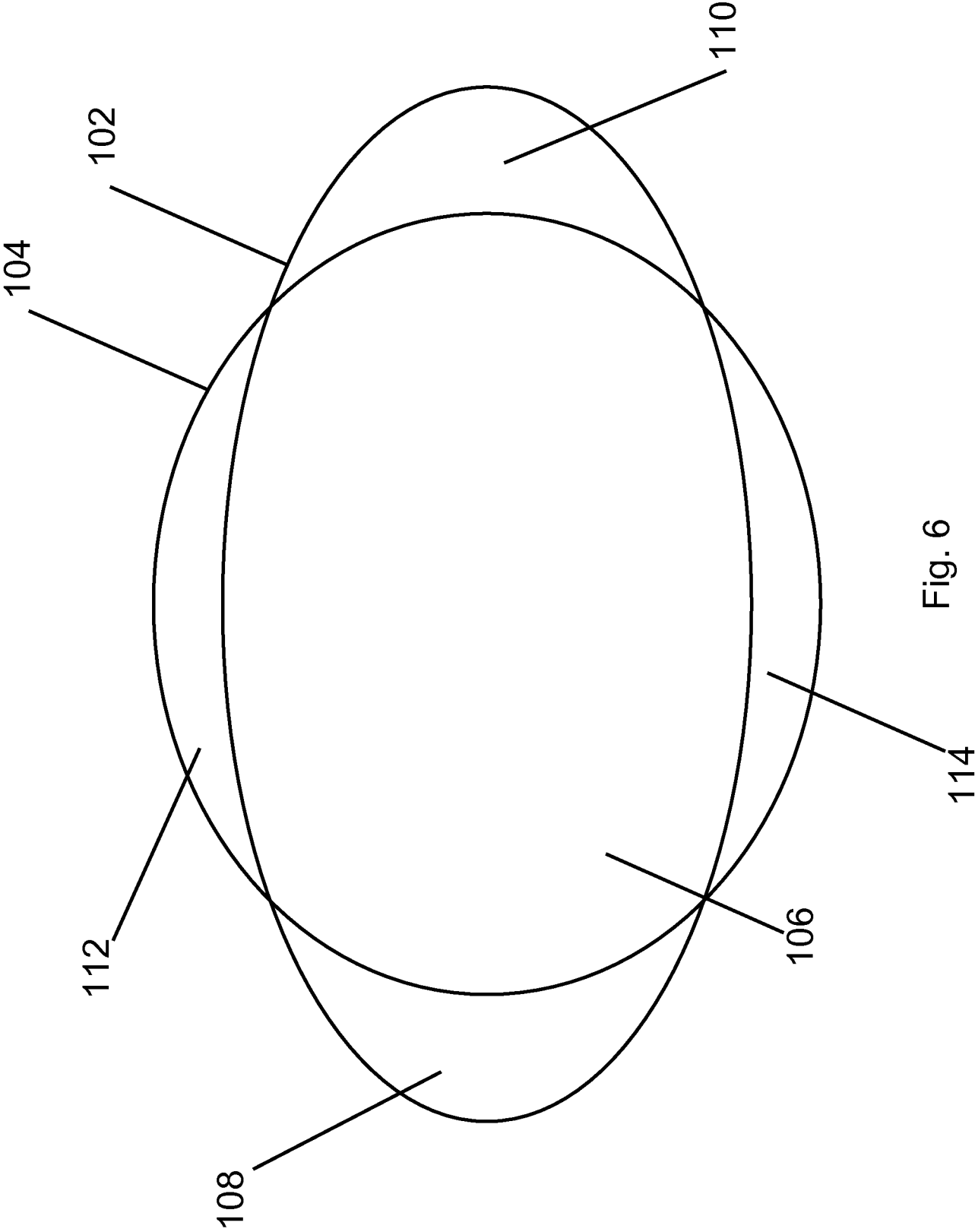


Fig. 5



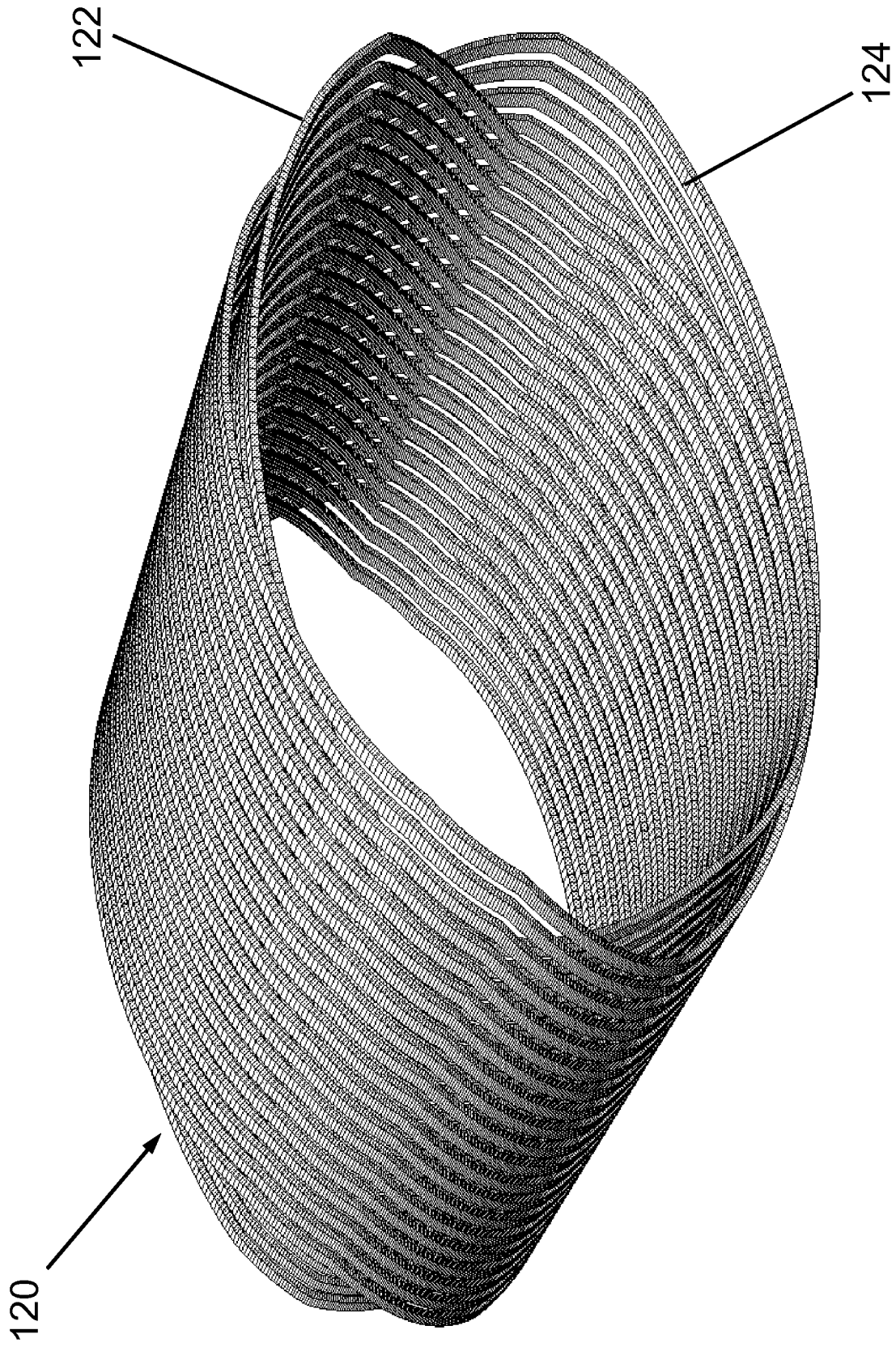


Fig. 7

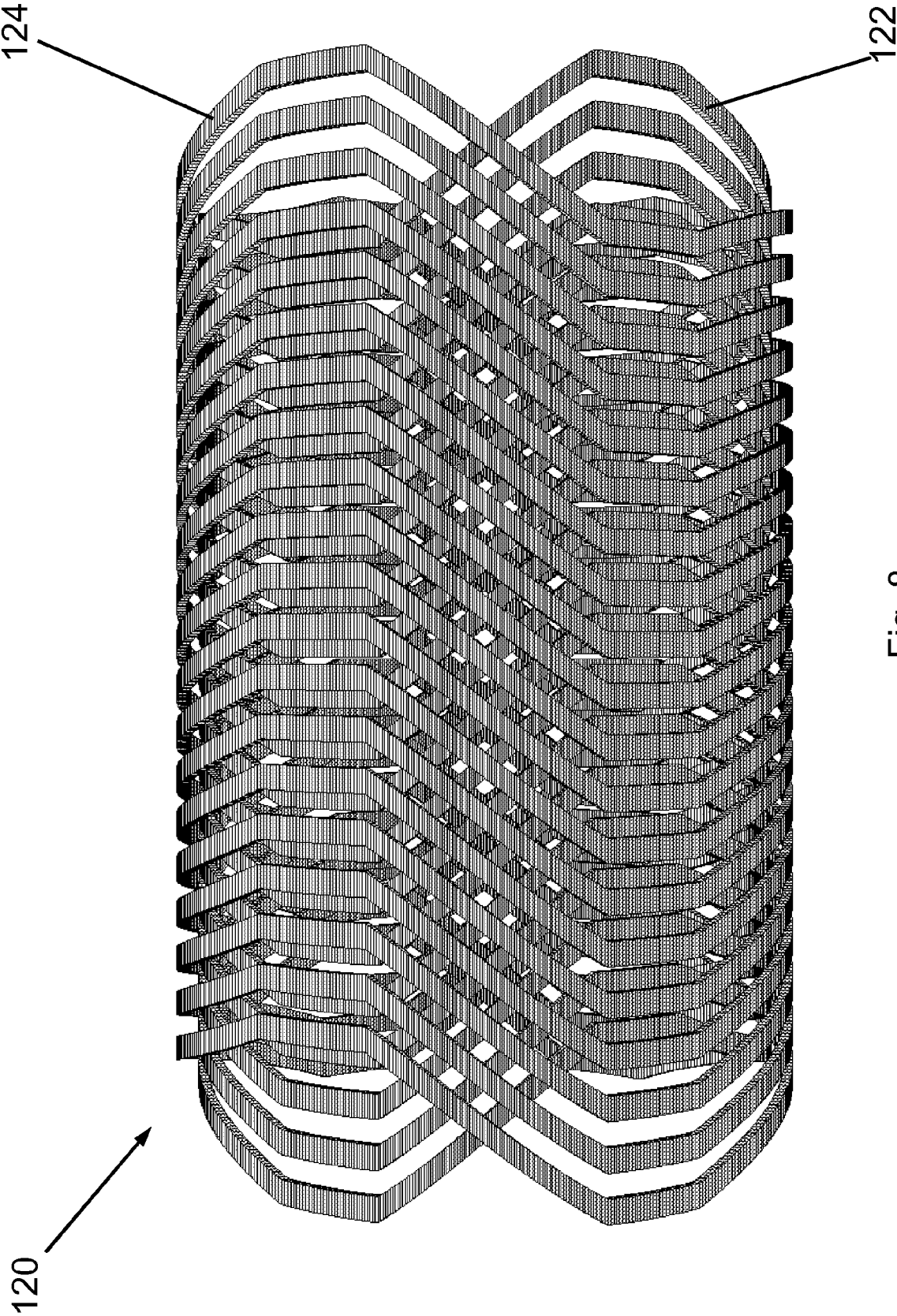


Fig. 8

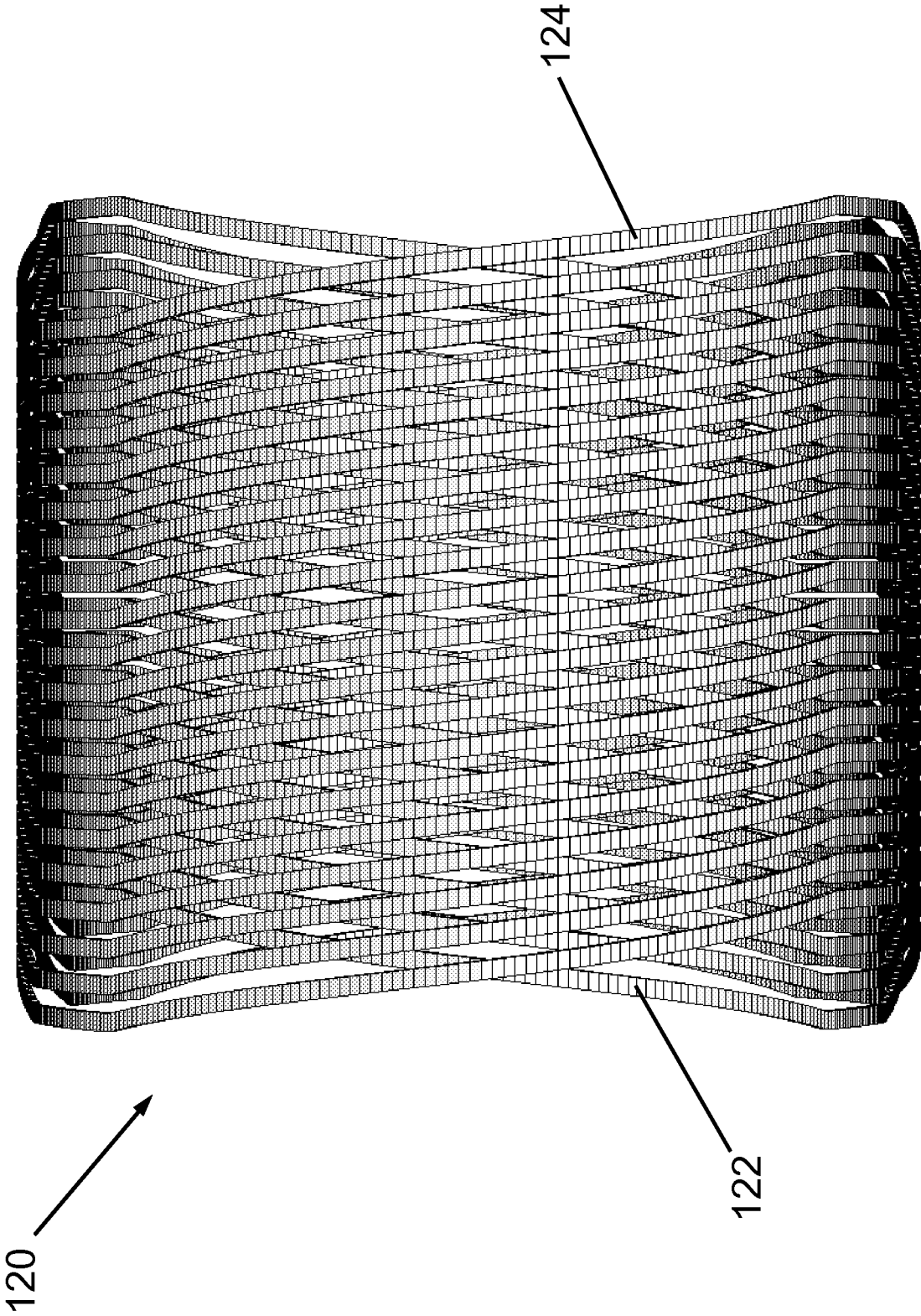


Fig. 9

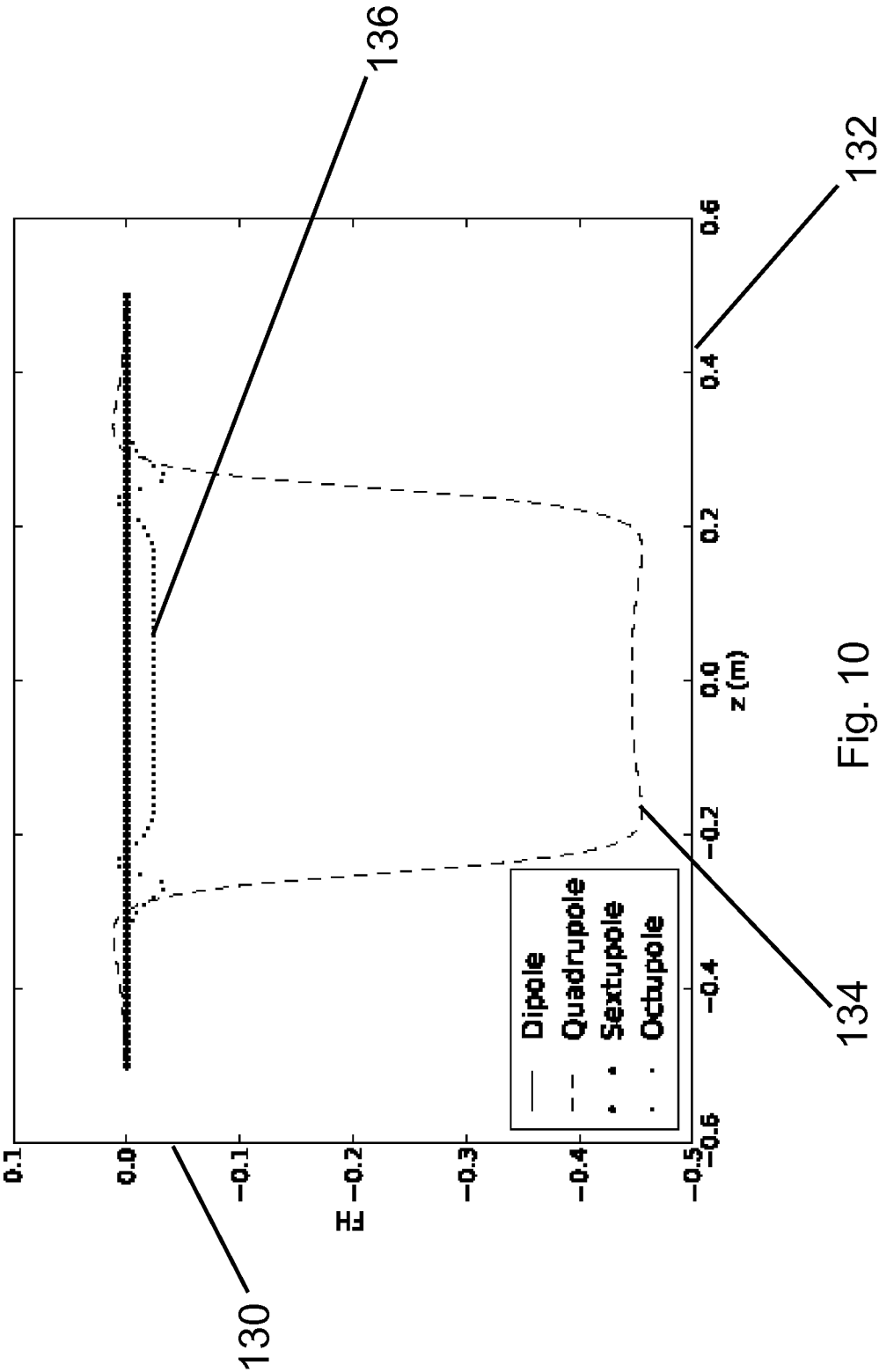


Fig. 10

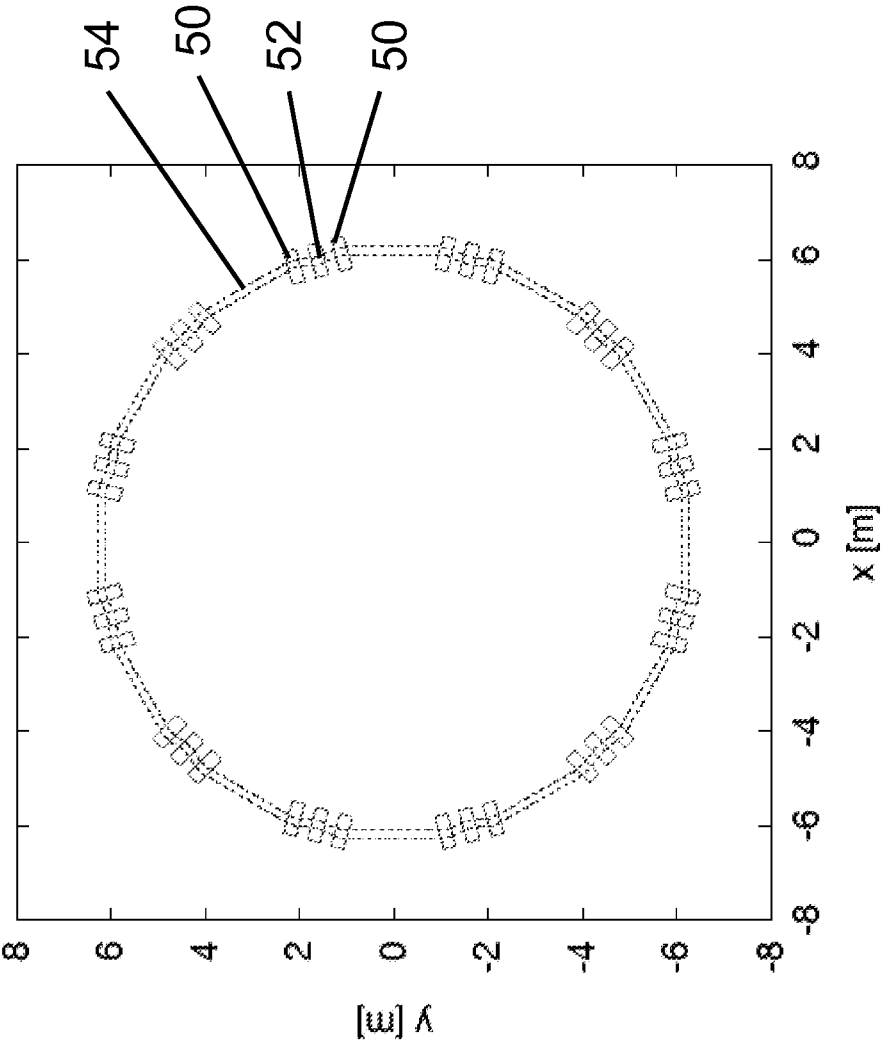


Fig. 11

# INTERNATIONAL SEARCH REPORT

International application No  
PCT/GB2012/050461

A. CLASSIFICATION OF SUBJECT MATTER  
INV. G21K1/093 H01F7/20  
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)  
G21K H01F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EP0-Internal, WPI Data

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages                                                                                                                                                                                                                                                                                                                           | Relevant to claim No. |
|-----------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------|
| X         | <p>MEINKEO R B ET AL: "Superconducting double-helix accelerator magnets", PROCEEDINGS OF THE 2003 PARTICLE ACCELERATOR CONFERENCE. PAC 2003. PORTLAND, OR, MAY 12 - 16, 2003; [PARTICLE ACCELERATOR CONFERENCE], NEW YORK, NY : IEEE, US, vol. 3, 12 May 2003 (2003-05-12), pages 1996-1998, XP010699515, DOI: 10.1109/PAC.2003.1288752 ISBN: 978-0-7803-7738-7 the whole document</p> <p>-----<br/>-/--</p> | 1-9,11,<br>12,17-23   |

☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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"&" document member of the same patent family

Date of the actual completion of the international search

30 May 2012

Date of mailing of the international search report

08/06/2012

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Authorized officer

Giovanardi, Chiara

# INTERNATIONAL SEARCH REPORT

International application No  
PCT/GB2012/050461

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages                                                                                                                                                                                                                                                                                                                                                                                                              | Relevant to claim No.                          |
|-----------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------|
| X         | <p>WITTE H ET AL: "Pamela Magnets - Design and Performance",<br/>PROCEEDINGS OF PARTICLE ACCELERATOR CONFERENCE (PAC 09), VANCOUVER, BC, CANADA, 4-8 MAY 2009,<br/>4 May 2009 (2009-05-04), pages 1-3,<br/>XP002626830,<br/>Retrieved from the Internet:<br/>URL:<a href="http://trshare.triumf.ca/~pac09proc/Proceedings_091005/papers/mo6pfp073.pdf">http://trshare.triumf.ca/~pac09proc/Proceedings_091005/papers/mo6pfp073.pdf</a><br/>[retrieved on 2011-03-04]<br/>the whole document</p> | <p>1,2,4-7,<br/>9,11,<br/>13-16,<br/>22-26</p> |
| X         | <p>US 6 921 042 B1 (GOODZEIT CARL L [US] ET AL) 26 July 2005 (2005-07-26)<br/>figures 1-3<br/>column 4, line 20 - column 11, line 2</p>                                                                                                                                                                                                                                                                                                                                                         | <p>1-12,<br/>17-23</p>                         |
| X,P       | <p>WO 2011/061537 A1 (ISIS INNOVATION [GB]; PEACH KEN [GB]; WITTE HOLGER [GB])<br/>26 May 2011 (2011-05-26)<br/>figures 1-2,4-5<br/>page 1, lines 1-10<br/>pages 3-4<br/>page 6 - page 21</p>                                                                                                                                                                                                                                                                                                   | <p>1-26</p>                                    |

# INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/GB2012/050461

| Patent document<br>cited in search report |    | Publication<br>date | Patent family<br>member(s) | Publication<br>date |
|-------------------------------------------|----|---------------------|----------------------------|---------------------|
| US 6921042                                | B1 | 26-07-2005          | NONE                       |                     |
| -----                                     |    |                     |                            |                     |
| WO 2011061537                             | A1 | 26-05-2011          | NONE                       |                     |
| -----                                     |    |                     |                            |                     |