

12

EUROPEAN PATENT APPLICATION

21 Application number: **89310664.1**

51 Int. Cl.⁵: **G21K 1/093, H05H 7/04**

22 Date of filing: **17.10.89**

30 Priority: **08.11.88 GB 8826162**

43 Date of publication of application:
16.05.90 Bulletin 90/20

64 Designated Contracting States:
DE FR GB IT

71 Applicant: **Watt, Frank**
89 Wroslyn Road
Freeland Oxford OX7 2HL(GB)

Applicant: **Grime, Geoffrey William**
3 Lawrence Road
Oxford OX4 3ER(GB)

72 Inventor: **Watt, Frank**
89 Wroslyn Road
Freeland Oxford OX7 2HL(GB)
Inventor: **Grime, Geoffrey William**
3 Lawrence Road
Oxford OX4 3ER(GB)

74 Representative: **Unwin, Stephen Geoffrey**
S.G. Unwin & Co. 2 North Street
Islip Oxford OX5 2SL(GB)

54 **A core for a magnetic multipole lens.**

57 The core (5) comprises at least four poles (1) between which a magnetic field is to be produced and a yoke (3) connecting the poles together and providing a return path for the magnetic circuit within the core (5), the core (5) being formed from a single piece of magnetic material so that the poles (1) and yoke (3) are integral with each other. A multipole lens may be formed using the core (5) with exciting coils made up of U-shaped conducting elements (6) and bridging pieces (7) positioned around the poles (1) and this may form part of a microprobe for focusing a beam of charged particles, eg protons, onto a target. The core (5) may be cut from a billet of magnetic material by a computer controlled wire spark erosion technique.

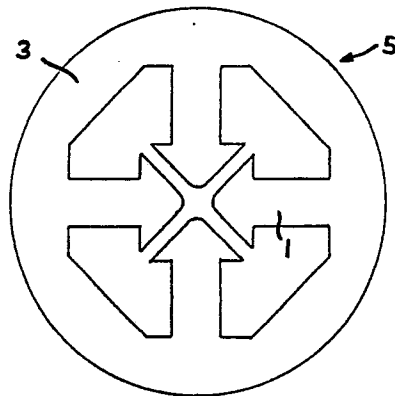


FIG. 3

Xerox Copy Centre

A CORE FOR A MAGNETIC MULTIPOLE LENS

This invention relates to a core for a magnetic multipole lens and more particularly to a quadrupole lens used to focus charged particles, for instance in a proton microprobe.

One of the main applications of magnetic multipole lens is for focussing high energy beams of ions in a microprobe which is a highly versatile tool used in analytical science to provide elemental analysis of samples and information on the spatial distribution and concentration of elements within the sample. The first working microprobe system was developed in the early 1970s and since then microprobes have been used as an analytical tool in a wide range of applications including the biological sciences, medicine, the earth sciences, metallurgy and industry, solid state physics and electronics, archaeology and many more.

A wide range of analysis techniques are used with a nuclear microprobe. The principle techniques are: particle-induced X-ray emission (PIXE), nuclear reaction analysis (NRA), Rutherford back-scattering (RBS) and elastic recoil detection analysis (ERDA).

The basis of a magnetic lens is that charged particles (eg. electrons, ions etc) can be focused using a magnetic field with the form:

$$\begin{aligned} B_r &= g r \cos 2\theta \\ B_\theta &= -g r \sin 2\theta \end{aligned} \quad \text{equation (1)}$$

(In cylindrical coordinates with the beam travelling along the z-axis where B is the magnetic field strength in Tesla, g is the field gradient in Tesla/m and r and θ are the cylindrical coordinates).

Such a field distribution can be generated by four magnetic poles arranged symmetrically about the z-axis and excited alternately North, South, North, South. This forms a quadrupole lens.

The effect of this lens is to converge the beam in one plane and diverge it in the orthogonal plane. Thus two or more lenses of alternating polarity are required to give convergent focusing in both planes simultaneously.

For use in a microprobe, the magnetic lens should focus the beam of particles into as small an area as possible whilst maintaining sufficient current (eg. several tens of picoamperes) through that area for the various analytical techniques which are used. Up to 1985, the spot diameter produced by such lenses had been reduced to 1 μ m diameter with a current of 80 pA of 4 MeV protons. In 1986 the applicants set an improved standard with a conventional quadrupole lens with 90% of a 25 pA beam estimated to be focussed within a 0.5 μ m sq.

A number of different systems have been considered for focusing beams of charged particles and others are being developed. Electrostatic lenses are considered to be impracticable as fields in the MV/m region would be required. The type of magnetic solenoid lens used in an electron probe has also been considered but it has been calculated that a 1 MeV proton probe would need 230 times the field used in a 30 KeV electron probe. Fields of this order cannot yet be produced although it is possible using superconducting coils to generate fields of several Tesla. Lenses using superconducting coils have been made and although initial results have not been totally successful, the technique is still being developed. A plasma lens consisting of ionised atoms and free electrons confined into a cylindrical shape using a suitable set of magnetic fields has also been constructed and development of this is continuing. The most successful focusing system to date has been the magnetic quadrupole lens and a cross-sectional view of a conventional quadrupole lens is shown in Figure 1.

This is constructed from four separately machined pole pieces 1. Exciting coils 2 are fitted to the pole pieces 1 and each pole piece is then fixed to the inside of a yoke 3, for instance by a bolt which passes through the yoke 3 and screws into a threaded hole provided in the pole piece 1.

The form of the magnetic field produced is determined by the shape and position of the pole pieces 1 and the yoke 3 forms the return path for the magnetic circuit as well as the mechanical support for the pole pieces 1. The magnetic circuit is energised by the exciting coils 2. Figure 1 shows the magnetic field produced in the aperture of the lens.

As mentioned above, the effect of a single quadrupole lens is to converge a beam in one place and diverge it in the orthogonal place so forming a line focus. This is illustrated in Figure 2. Two or more lenses are thus required to focus a beam to a spot and this is typically performed using a doublet or triplet of quadrupole lenses. A number of aberrations limit the spot size to which a beam can be focussed by a

quadrupole lens. The dominant intrinsic and parasitic aberrations are: astigmatism due to the differing focusing strengths in orthogonal planes, chromatic aberration due to the energy spread of particles within the beam to be focused, spherical aberration which arises as a result of the slightly different forces experienced by particles travelling at an angle to the axis of the lens, aberrations due to misalignment of the quadrupoles relative to the optical axis of the system and aberrations due to the quadrupole construction.

Aberrations due to quadrupole construction of a conventional lens arise as a result of imperfections in the quadrupole field itself. Ideally, the magnetic (or electrostatic) field lines would be perfect hyperbolae generated by hyperbolic pole faces arranged with true four-fold symmetry. In practice, however, it is not possible to construct these ideal profiles. The pole faces must be truncated at some point to allow space for the coils, while for ease of machining the pole faces may be made up from cylindrical or flat surfaces. In addition, constructional tolerances can lead to errors in the pole profile and deviation from symmetry due to imprecise pole positioning. Aberrations arise from departures from four-fold symmetry in the mechanical construction of the poles, departures from four-fold symmetry in the magnetic circuit of the lens (including magnetic properties of the material of the poles and yoke and of the exciting coils) and departures from the ideal hyperbolic pole profile.

Such inaccuracies distort the field lines and lead to aberration of the beam spot. The distortion of the field may be treated mathematically as a superposition of higher-order field harmonics on the basic quadrupole field.

These are field components with higher orders of symmetry; for example, an octupole component may be envisaged as having been produced by eight alternating poles arranged symmetrically about the axis.

The relative strength of the contaminant harmonic field components increases rapidly at points further from the axis, and so one way of reducing their effect is to use quadrupoles with a bore much larger than the predicted beam diameter. This will also entail an increase in the size of the coil windings to compensate for the extra air gap, so it may be necessary to compromise between harmonic effects and quadrupole size. Other precautions include careful design of the magnetic circuit to avoid saturation at high fields which could distort the fields in an unpredictable manner, careful pole face shaping to reduce harmonic contamination and, of course, very fine tolerances in the machining and location of the poles.

The quality of imaging depends on the quadrupole field purity, especially for nuclear microprobe applications where it is crucial to minimise the higher order multipole contamination.

The construction of a conventional quadrupole lens will be considered in more detail below:

The quadrupole lenses must be constructed so that the stringent requirements of a pure quadrupole field which can be precisely aligned are achieved. The task of designing a quadrupole can conveniently be approached in three stages: (i) determining the basic dimensions of the lens to achieve the required focusing performance, (ii) determining the correct pole shape to produce a field with the required quality and mounting the poles and coils inside the yoke with the necessary degree of symmetry, and (iii) mounting the complete lens on a rigid base which permits precise alignment. These three stages will be considered in turn.

The basic dimensions must first be determined; in particular, the length and the radius of the aperture are important, since these will affect all subsequent operations. The effective length and the focusing strength of the lenses are determined by the space available for the instrument, the desired imaging properties and the target distance.

On the other hand, the bore radius of the lens does not affect the imaging directly, and so may be chosen from a range of values. The following factors affect the choice of radius:

(1) The effect of higher-order contamination increases rapidly as one moves away from the axis; the radius should therefore be made much larger than the predicted beam size within the lens. This can only be studied in detail by a full numerical analysis of each case, but it has been found that a radius of five to ten times the beam radius has not shown any effects directly attributable to harmonic contamination.

(2) In competition with this, as the radius increases, the pole tip field required to produce a given focusing strength increases, and so an upper limit is set by the field level at which magnetic saturation occurs in the iron of the poles.

(3) As a consequence of (2), the number of ampere-turns of the coils, and hence the power dissipated by the current, increases with radius, and may introduce a requirement for cooling for high-field operation.

(4) The ratio of radius to effective length affects the longitudinal field profile of the lens; as the radius becomes comparable with the length, the regions of fringing field at the ends of the lens dominate. A small increase in spherical aberration has been found when the fringing field region is a significant fraction of the effective length.

(5) From a purely practical point of view, the total mass and hence expense of the coils and of the

iron increase with radius, but, conversely, assuming that machining tolerances do not depend on the size of the job, the fractional precision of the work improves.

It is obvious that the final radius of the lens will be a compromise between all these factors. In most cases, however, the fields required to focus MeV protons are relatively weak, and this relaxes the requirements relating to iron saturation and power dissipation.

Once the dimensions of the lens have been determined, the next stage of the design is to select the shape of the pole face. The ideal pole profile would be hyperbolic, with the pole extending to infinity. Obviously this is not possible, and the poles must be truncated to allow space for the coils to be mounted. In addition, the precise machining of hyperbolic surfaces is difficult even with numerically controlled equipment. The penalty of departing from the ideal profile is the introduction of higher-order multipole harmonic contamination, as discussed above.

Assuming perfect four-fold symmetry in the construction of the lens, the pole profile only affects the 12- and 20-pole components, of the field. Departures from symmetry, however, introduce lower-order components which can have a large effect on the imaging, hence rather than absolute accuracy in the production of the pole profiles, more emphasis should be placed upon ensuring that all four poles are identical and are mounted with precise four-fold symmetry.

The shape of the yoke is relatively unimportant, since it simply provides a return path for the magnetic flux. It also provides mechanical support for the poles and coils, so it should be designed with this requirement in mind. In particular, the use of a cylindrical yoke simplifies the rotational adjustment of the lens, and the yoke should have sufficient rigidity to avoid distortion when it is resting on its mounting.

The material of the yoke and poles should be high-quality magnet iron selected for high saturation fields and high permeability. Typical lenses use SKF 'Remko' steel for the poles and 'Maximag' for the yoke, and some quadrupoles are made from 'Vacoflux' magnet steel. It is important that the material should be homogeneous, since variations in permeability of saturation field could also cause localised fluctuations in the quadrupole field.

In order to preserve symmetry, it is also important that the coils are identical. The number of ampere-turns per coil can be calculated from a knowledge of the radius and the required strength; this may be achieved either with few turns and high current or many turns and low current. The use of a few turns of thick wire is preferred, since the turns can be laid individually by hand to ensure a consistent winding profile. Typical coils each have 19 layers of 27 turns of $1 \times 2 \text{ mm}^2$ cross section wire, while coils of 3250 turns have also been used.

In the quest for absolute symmetry, the assembly of the various components of the lens takes place from the centre outwards, so that the pole position is firmly established before the yoke is fitted. The position of the pole tips are established by means of precision, jig-bored, phosphor-bronze rings before the heels of the poles are ground to match the inside surface of the yoke. Alternatively the poles may be located by means of precision spacers rather than by rigid fastenings. This method avoids some of the stresses which may result from a rigid assembly.

The final stage of construction is to make a support stage for the lens which will allow the orientation to be set to the required degree of accuracy. Ideally, it should be possible to make all six adjustments independently (three direct ions of linear motion and three direction of rotation about the centre), but a support of this type would be unnecessarily complex, especially for large quadrupoles whose mass may be in the region of 100kg. In practice, the most critical adjustment is the rotation about the axis, so one approach is to mount the cylindrical quadrupole on roller bearings on a sub-table. The quadrupole can then be rotated by means of a micrometer driving a spring-loaded lug on the yoke, while the sub-table can be mounted on three adjustable ball-bearing feet to allow vertical and horizontal adjustment of translation and tilt. This system has been used with some success, although it is obvious that there is considerable scope for mechanical variation in the design of quadrupole mounting systems.

Further details of the construction of conventional quadrupole lenses and on many of the other matters referred to above are given in the book "Principles & Applications of High-Energy Ion Microbeams" (edited by F.Watt and G.W.Grime and published in 1987 by IOP Publishing Limited of Bristol, England) the contents of which are incorporated herein by this reference.

As explained above, one of the significant factors limiting the spot size to which a beam particles can be focused are the imaging aberrations due to imperfect construction of the quadrupole lens. Steps have been taken to minimise this by constructing the pole pieces and yoke to yet finer tolerances by very accurate machining and fitting them together with yet higher accuracy using high precision jigs. Other attempts have been made to overcome the problem by the use of compensating fields to counteract the aberrations. These approaches have been successful to a limited degree but it is difficult to achieve yet further reductions in spot size and it is also increasingly difficult to construct the two, three or more lens

needed to focus the beam with a similar degree of accuracy.

The present invention represents a radical departure from such developments and avoids or reduces many of the problems discussed above. The present invention provides a core for a magnetic multipole lens, the core comprising at least four poles between which a magnetic field is to be produced and a yoke connecting the poles together and providing a return path for the magnetic circuit within the core, the core being formed from a single piece of magnetic material so that the poles and yoke are integral with each other.

Preferred features of the invention will be apparent from the following description and from the subsidiary claims of the specification.

The invention will now be further described, merely by way of example, with reference to the accompanying drawings, in which:

Figure 1 in a cross-sectional view of a conventional quadrupole lens,

Figure 2 in a diagram illustrating the effect of a single quadrupole lens on a beam of particles entering from the left;

Figure 3 is a cross-sectional view of the core of a quadrupole lens according to an embodiment of the invention;

Figure 4A is a perspective, exploded view of the components making up a coil to be used with the core shown in Figure 3, and Figure 4B illustrates the manner in which a continuous coil is formed by connection of these components; and

Figure 5 is a perspective view of a triplet of quadrupole lenses each comprising a core as shown in Figure 3 and coils constructed as shown in Figure 4.

The core 5 shown in Figure 3 is made from a single piece of magnetic material such as SKF 'Remko' high quality magnet iron made by Uddeholm Strip Steel AG of Sweden. As the core is made from a single piece of iron, errors due to the assembly of individual components are eliminated so deviations from exact symmetry are reduced.

Also, since there are no joints between the poles 1 and the yoke 3, the magnetic circuit is continuous (variable magnetic flux leakage caused by air gaps or machining at joints can cause asymmetry in the magnetic field).

As will be further described below, these advantages lead to a significantly improved field purity for the integral construction.

The core is formed by cutting it from a billet of magnetic material by a computer numerically controlled (CNC) wire spark erosion technique using an Agiecut wire cutting machine manufactured by Agie of Switzerland. In this technique, a wire is held adjacent the workpiece, immersed in a liquid such as water, and a voltage is applied to the wire causing sparking along its length between itself and the workpiece. This sparking erodes the workpiece and the wire is continually fed along its length. The position of the wire and hence the shape of the profile cut from the workpiece is determined by movement of guides positioning the wire under the control of a computer. The cutting can be performed within tolerances of less than 5 microns and complex shapes can be cut by appropriate movement of the wire.

The core is formed by the following steps:

1) A cylindrical billet of high purity magnet steel (eg. SKF 'Remko') is turned to approximately the length and diameter required.

2) The internal structure of the core is then roughly machined to isolate the four pole regions.

3) The machined billet is heat-treated to the manufacturer's specification to relieve stress caused by the rough machining and to restore its magnetic properties. Details of the heat treatments of Remko are provided in the manufacturer's information sheets

4) After heat-treatment, it is given a final light machining to the correct length and diameter.

5) The internal profile of the core is cut using CNC wire erosion. The pole profile is cut so as to provide a hyperbolic central region with the faces of adjacent poles parallel to each other as this permits the use of magnetic field measuring devices (eg. NMR probe) to stabilise the field.

6) The core is then Nickel plated to provide a durable rust-free finish.

7) Finally, the poles are insulated with glass-fibre tape and coils are assembled on the poles from copper, U-shaped laminations insulated with glass fibre spacers.

The coils mentioned above will be described in more detail with reference to Figure 4. Figure 4A shows U-shaped laminations 6 and bridging pieces 7 made from copper strips. The bridging pieces 7 are soldered between the end of one lamination and the opposite end of the adjacent lamination as indicated by the arrows in the Figure. Glass fibre spacers 8 are positioned between the laminations 6 to insulate them from each other. It will be appreciated that a stack of such laminations 6 and spacers 8, together with the connecting pieces 7, form a continuous coil as shown in Figure 4B. A coil consisting of 12 such turns of

copper strip is able to carry a current of 50-80A.

It is, of course, necessary to construct the coil on the poles in this manner since it is not possible to fit a ready-made coil onto the poles of the core as would be done in a conventional quadrupole lens by fitting the coils onto the poles before the poles were fixed to the yoke. This construction also has the advantage that the laminar design provides a large finned area which is efficient in dissipating heat from the coil.

As an alternative to the above, it would be possible to wind a coil on the poles but this would need to be done with a high degree of accuracy to maintain the four-fold symmetry of the lens.

The wire erosion cutting technique allows the core to be much more accurately formed than has been possible with conventional machining techniques. The accuracy of cutting is also easier to reproduce so several cores can be cut to a similar degree of accuracy. As cutting of the core profile is done in a single operation, rather than having to machine several components separately and then fit them together, it is also quicker and less expensive. The wire spark erosion cutting technique also allows complex shapes to be accurately cut within confined spaces so it is possible to form the poles with hyperbolic faces which are very difficult to form by conventional machining techniques.

Figure 5 shows a perspective view of a triplet of quadrupole lenses each having one-piece cores and coils formed from copper laminations as described above. Each lens is mounted in a stage which allows precise adjustment of its position by horizontal and vertical translation and tilt (with a 5 micron accuracy) and axial rotation (within a 50 micro-radian accuracy) to permit the lenses to be aligned with each other. The stages are of conventional design and so will not be described further. The lenses are operated by conventional, matched power supplies.

Measurement of the imaging aberrations resulting from quadrupole cores formed in the manner described above using the grid shadow method show negligible parasitic aberrations below fifth order. Details of the grid shadow method are given in papers by D.N.Jamieson and G.J.F.Legge in Nucl. Instr. and Meth. B(1988).NIMB 08781 and B29(1987) 544. With quadrupole lenses constructed in the manner described with a 15mm aperture, a 150pA beam of protons has been focussed to a spot of 0.5µm diameter. Compared to the best results previously published of a 150pA beam focused to a spot of 1 micron diameter, this represents a four-fold increase in performance.

The almost complete absence of second order parasitic aberration from the lens system represents an important advance since this aberration degrades the resolution of microprobes at relatively small lens acceptance angles and absence of second order aberrations has not previously been reported.

Multipole lenses are also used as correctors for various aberrations in ion or electron optical systems. In these devices the field is given by:

$$B_r = gr^{n-1} \cos(n\theta)$$

$$B_\theta = -gr^{n-1} \sin(n\theta)$$

(for a 2n-pole field where $n > 2$)

This field is generated by 2n alternating poles arranged symmetrically about the axis. Magnetic quadrupole and multiple lenses are also used in beam transport systems for high energy ion beams for focusing ion beams to very small diameters (≤ 1 micron) for use in nuclear probes. The one-piece core and magnetic multipole lenses using such a core may also be used in these applications.

Claims

1. A core (5) for a magnetic multipole lens, the core comprising at least four poles between which a magnetic field is to be produced and a yoke connecting the poles together and providing a return path for the magnetic circuit within the core (5), the core (5) being formed from a single piece of magnetic material so that the poles and yoke are integral with each other.

2. A core (5) as claimed in claim 1 in which the poles (1) have an hyperbolic profile.

3. A core (5) as claimed in claim 1 or 2 in which opposing faces of adjacent poles have substantially parallel faces to allow nuclear magnetic resonance measurement of a uniform magnetic field generated therebetween.

4. A core (5) as claimed in claim 1, 2 or 3 in which recesses are provided in the poles for receiving exciting coils and the yoke is substantially circular.

5. A multipole lens comprising a core (5) as claimed in any preceding claim with exciting coils positioned around the poles.

6. A multipole lens as claimed in claim 5 capable of producing a field which when measured by the grid shadow method shows substantially no parasitic aberrations below fifth order.

7. A multipole lens as claimed in claim 5 or 6 in which the coils comprise substantially U-shaped

conducting elements (6) separated by insulating spacers (8), adjacent elements being electrically connected by bridging pieces (7).

8. A multipole lens as claimed in claim 7 in which there is an air space between adjacent elements (6) of the coil to allow for dissipation of heat.

5 9. A multipole lens as claimed in any of claims 5 to 8 forming part of a microprobe for focusing a beam of charged particles, eg protons, onto a target.

10. A method of forming a core (5) as claimed in any of claims 1 to 4 in which the core (5) is cut from a billet of magnetic material by means of a computer controlled wire spark erosion technique within tolerances of 5 microns or less.

10 11. A method as claimed in claim 10 in which the billet is first machined to substantially the required shape and is then heat treated to relieve stress caused by the machining and to restore its magnetic properties before the profile of the poles is cut by the wire spark erosion technique.

15

20

25

30

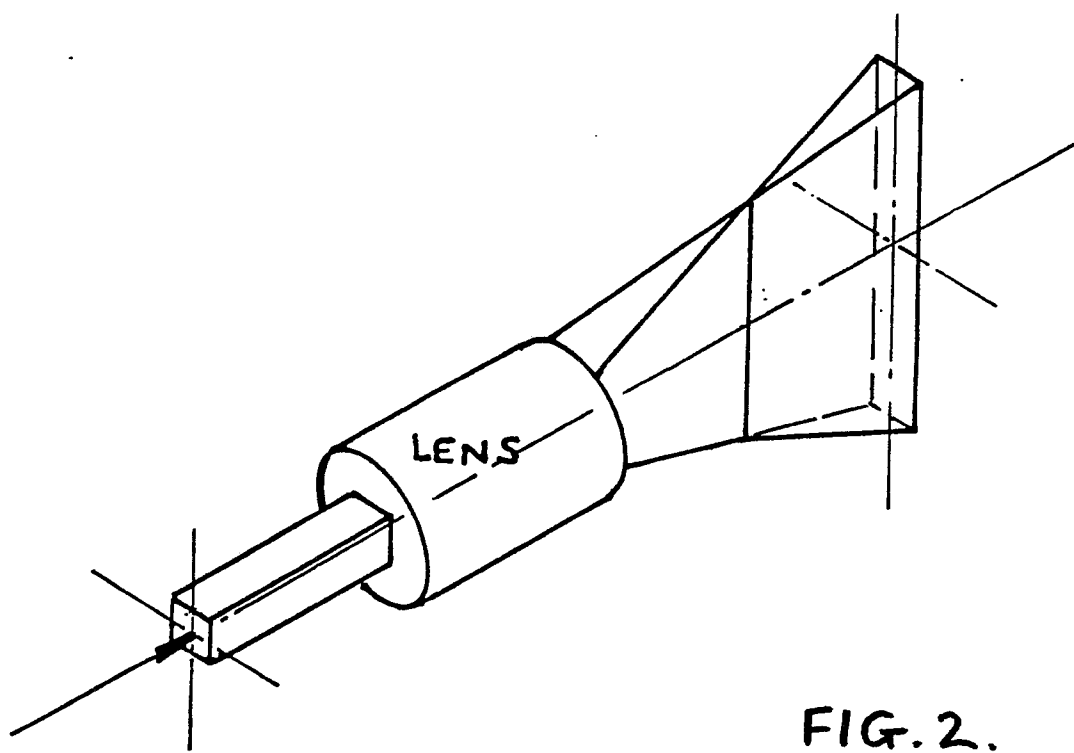
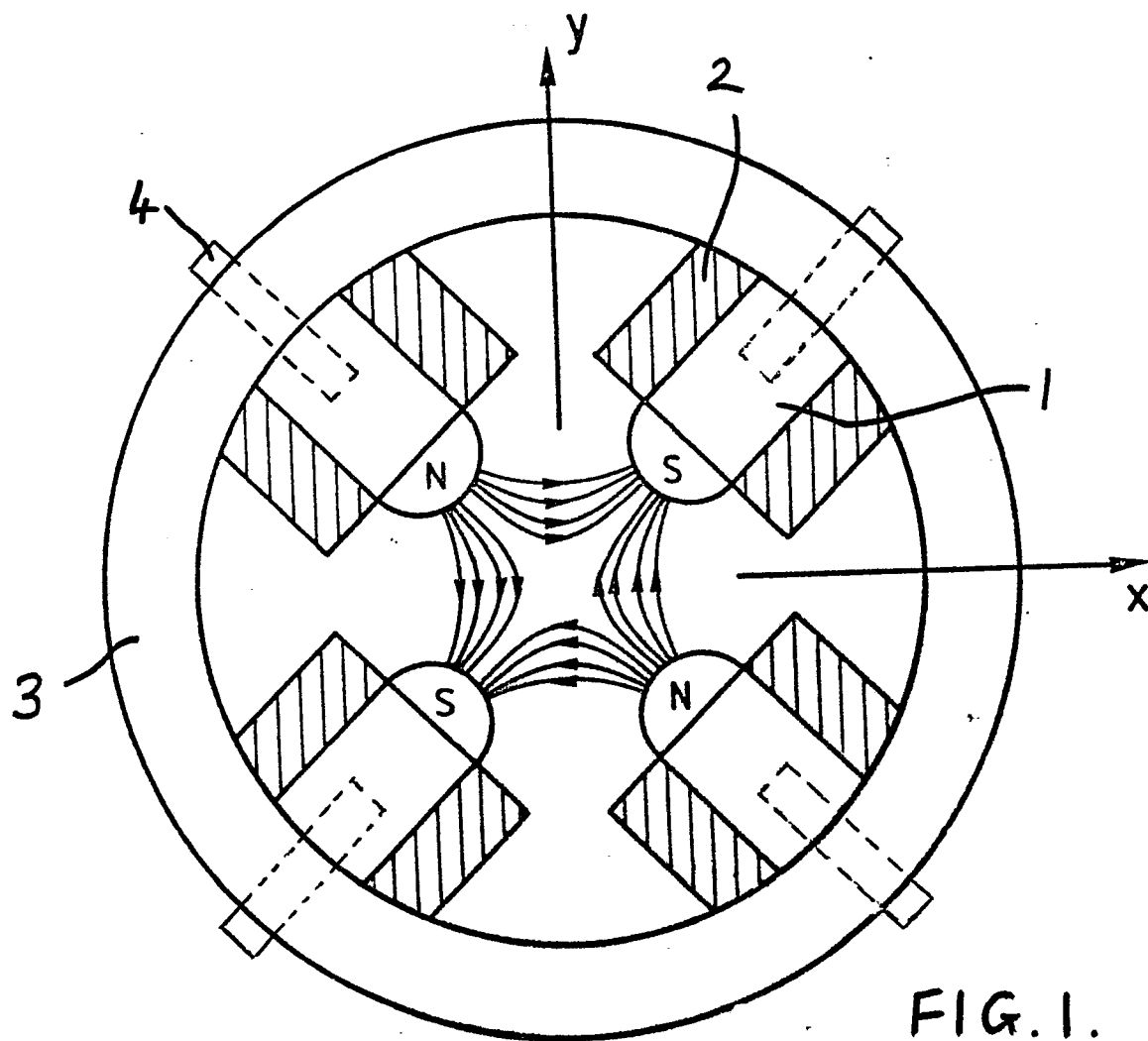
35

40

45

50

55



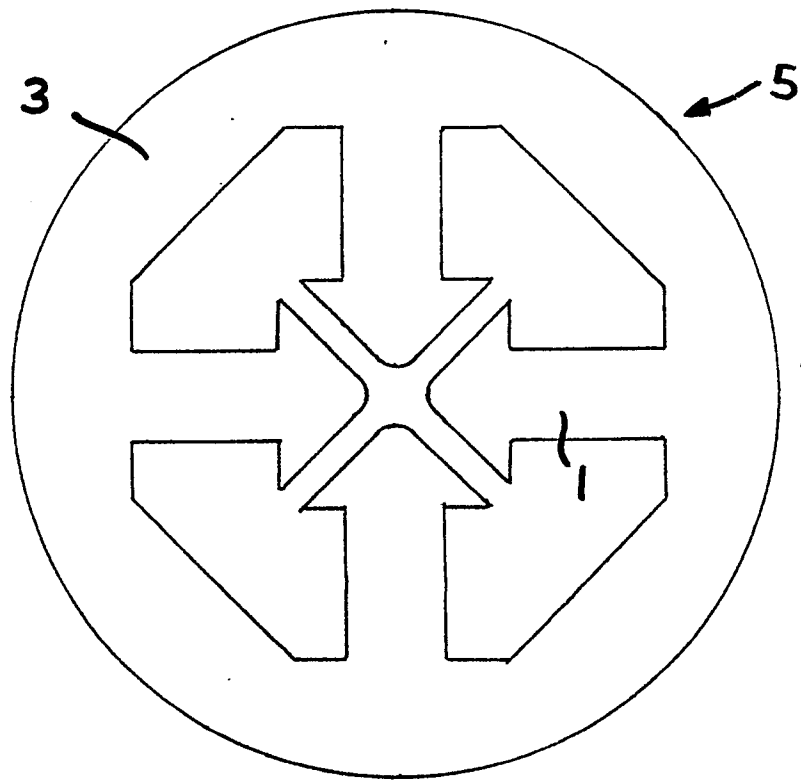
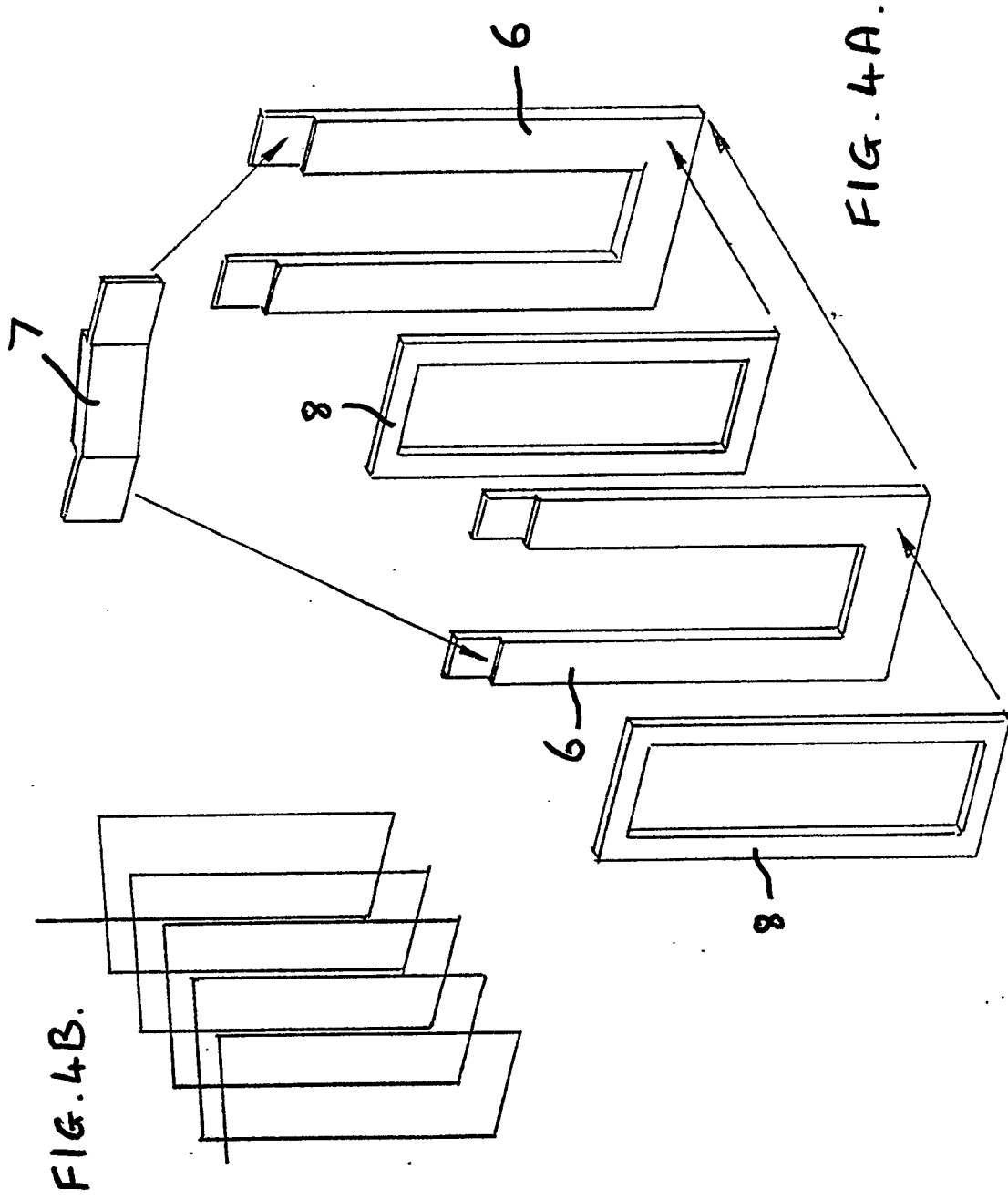


FIG. 3



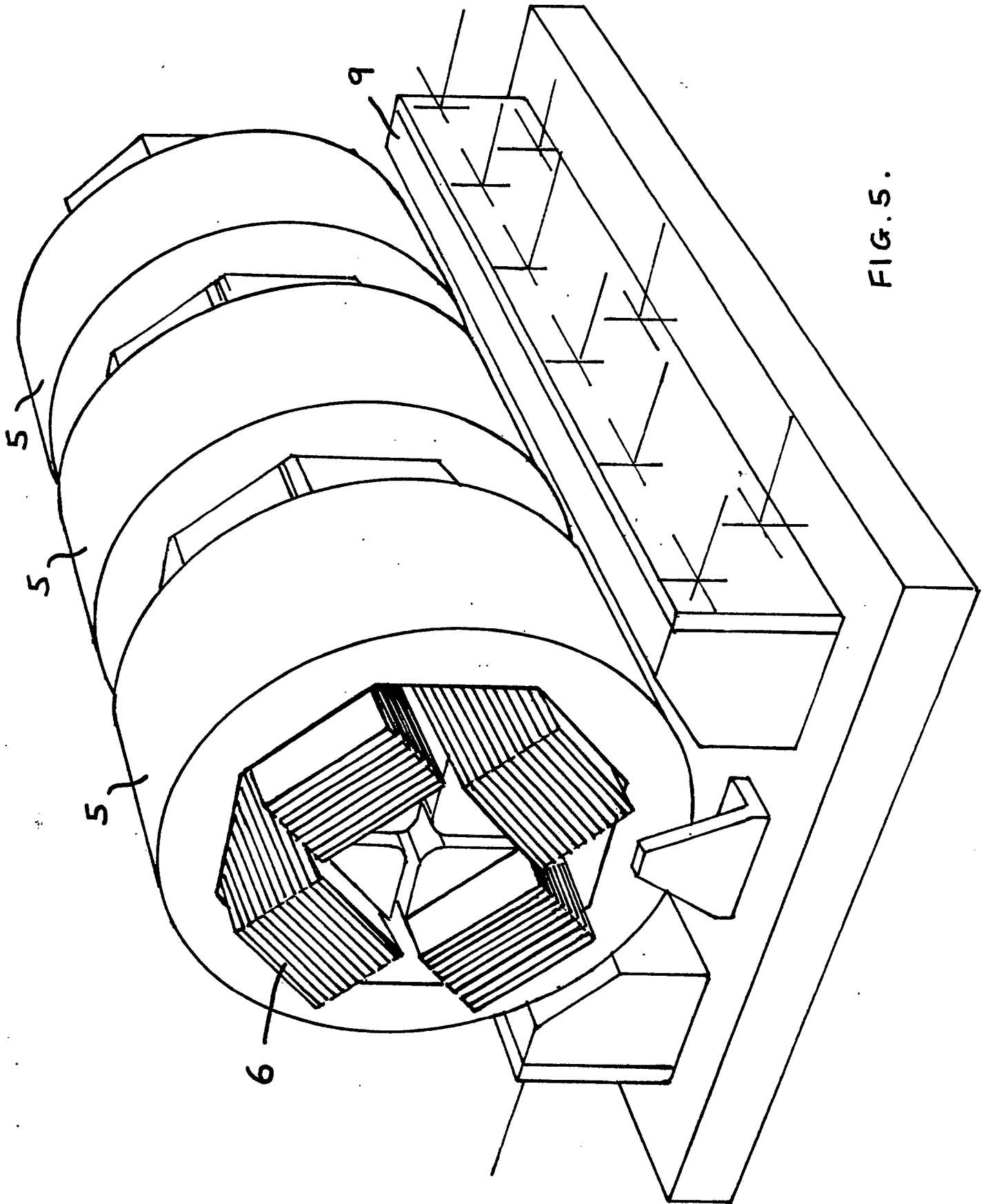


FIG. 5.



DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.5)
P,X	NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH, vol. B40/41, part I, 2nd April 1989, pages 669-674, Elsevier Science Publishes B.V., Amsterdam, NL; D.N. JAMIESON et al.: "The new Oxford scanning proton microprobe analytical facility" * Abstract; page 672; figure 4 * ---	1-9	G 21 K 1/093 H 05 H 7/04
A	LU-A- 46 306 (ACEC) * Whole document; figures 1,2 * ---	1,4,5	
A	US-A-3 482 136 (J.C. HERRERA) * Column 2, lines 16-57; figures 2,3 * ---	1,4,5	
A	DE-A-1 907 342 (NAGEL) * Page 4, figures 2,4,6 * ---	1,3,9	
D,A	"Principles & applications of high-energy ion microbeams", 1987, pages 122-124, Ed. E. WATT and G.W. GRIME; IOP Publishing, Bristol, GB * Whole document * -----	1-9	
			TECHNICAL FIELDS SEARCHED (Int. Cl.5)
			G 21 K H 05 H H 01 J
The present search report has been drawn up for all claims			
Place of search THE HAGUE		Date of completion of the search 12-02-1990	Examiner ERRANI C.
CATEGORY OF CITED DOCUMENTS X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document			