United States Patent

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[33] **Switzerland**
[31] **8153/68**

[54] **MAGNETIC LENS DEVICE FOR CORPUSCULAR RAY APPARATUS OPERATING UNDER VACUUM**
6 Claims, 5 Drawing Figs.

[52] **U.S. Cl.** **335/210,** 335/216, 250/49.5
[51] **Int. Cl.** **H01f 7/00**
[50] **Field of Search** 335/210, 216; 250/49.5

[56] **References Cited**

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ABSTRACT: A magnetic lens device for corpuscular ray apparatus to operate under vacuum is equipped with a pair of tubular shielding cylinders of superconductive material coaxially surrounding the lens axis and spaced from each other along said axis. Cryogenic means are thermally connected with the cylinders, and lens windings surround the cylinders for generating a magnetic field. The respective cylinders terminate in end faces directed toward each other and defining between each other a lens gap in which the cylinders concentrate the field near the axis. According to the invention proper, the shielding cylinders comprise respective end portions of superconductive material of higher current-carrying capacity than the remaining portion of each cylinder, said end faces at said lens gap being formed by said respective end portions.

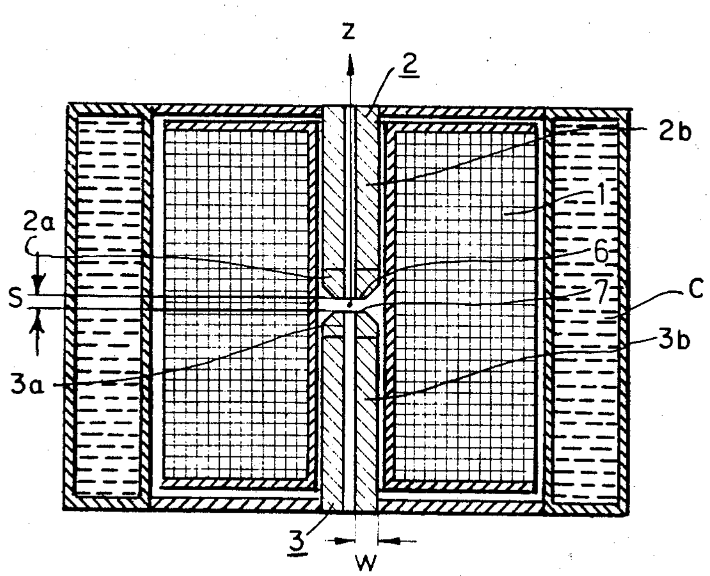


Fig. 1

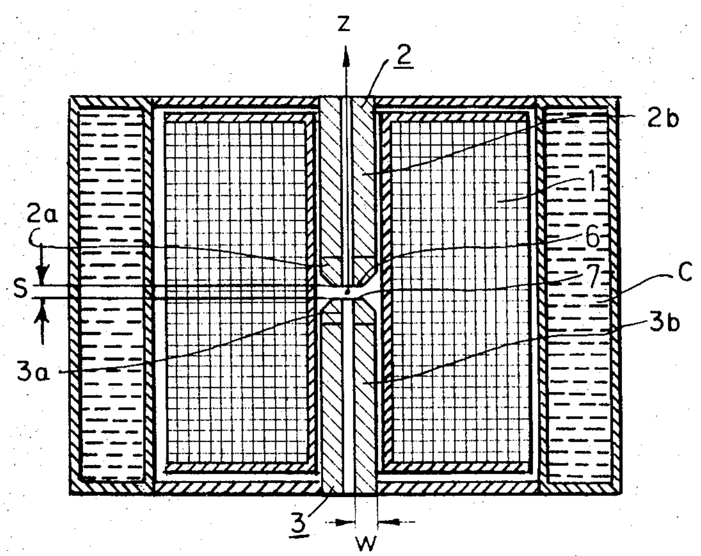


Fig. 2

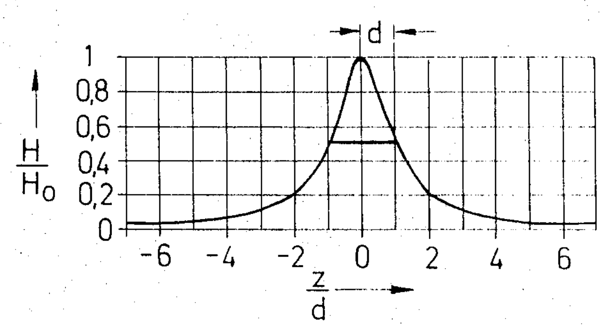


Fig. 3

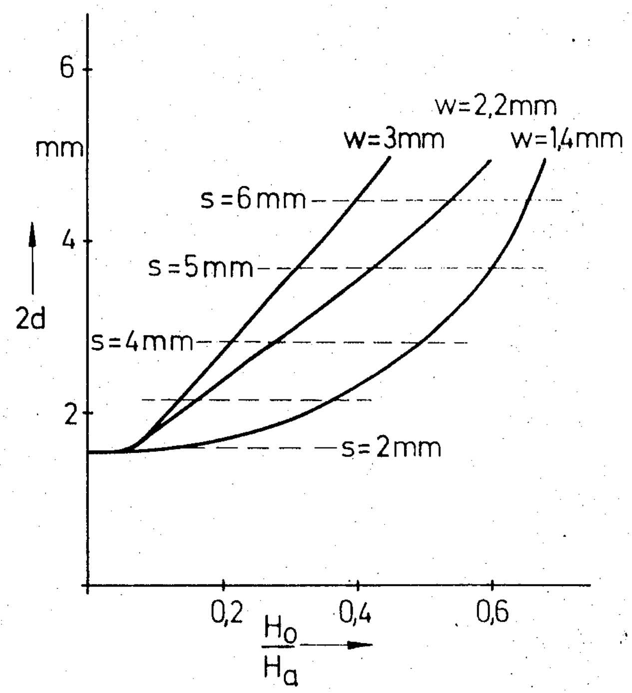

6
mm
4
2d
2
w=2,2mm
w=3mm
w=1,4mm
s=6mm
s=5mm
s=4mm
s=2mm
0,2
0,4
0,6
$\frac{H_o}{H_a}$

Fig. 4

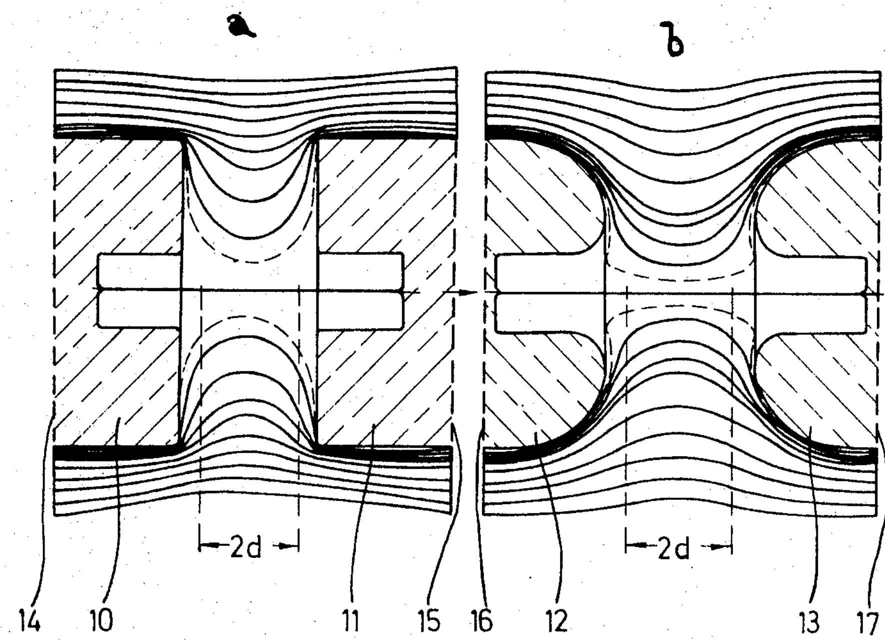
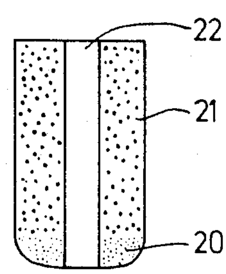


Fig. 5



MAGNETIC LENS DEVICE FOR CORPUSCULAR RAY APPARATUS OPERATING UNDER VACUUM

Our invention relates to magnetic lenses for electron microscopes and other corpuscular ray apparatus that are to be evacuated evacuated when in operation. More particularly, the invention relates to a magnetic lens device of a type equipped with two shielding cylinders coaxially spaced from each other in coaxial relation to the lens axis and in thermal connection with a cryogenic medium. By means of the shielding cylinders the magnetic lens field produced by electric flowing through the lens windings is concentrated in the region where the corpuscular ray passes through the lens gap between the two shielding cylinders, this gap being so dimensioned that for a given value of magnetic field strength outside of the lens gap and outside of the shielding cylinders, the maximum value of field strength within the lens gap and the field gradient in the lens gap along the axis conjointly produce an aperture error constant of the lens device below a predetermined permissible limit value. A lens device of this type is illustrated and described in detail in the copending U.S. Pat. application Ser. No. 648,623, of Zerbst et al., filed June 26, 1967.

It is an object of the present invention to improve such lens devices by further increasing, under otherwise comparable conditions, the concentration of the lens effect in the immediate vicinity of the lens axis within the lens gap. Another object is to simultaneously minimize the possibilities of instabilities of operation as may result from excessively high critical current densities.

To achieve these objects and in accordance with a feature of the invention, the two hollow cylindrical shielding structures that form part of the lens device and are spaced from each other along and in coaxial relation to the lens axis to establish the lens gap between each other, have their respective end portions adjacent to the gap face constituted by superconductor material of higher current-carrying capacity than the remaining portion of each shielding cylinder. Consequently the end portions have a particularly great shielding effect, whereas the other portions of the cylinders are less effective on account of their lower current-carrying capacity. As a result, while a penetration of the magnetic field into the high conductivity portions adjacent to the gap faces of the two cylindrical structures is virtually prevented, the field can penetrate more or less into the other portion of each shielding cylinder without impairing the imaging properties of the lens.

The invention will be further described with reference to the accompanying drawings, in which:

FIG. 1 shows schematically and in diametrical section an embodiment of a lens device according to the invention by way of example;

FIGS. 2 and 3 are graphs explanatory of the operation of such a lens device;

FIG. 4*a* and FIG. 4*b* show respectively a sectional and schematic view of the magnetic field line configuration occurring with planar gap faces and properly rounded gap faces respectively; and

FIG. 5 is a sectional view of one of the cylindrical shielding structures in a lens device according to the invention such as the one shown in FIG. 1.

The lens device shown in FIG. 1 is designed for operation as an objective lens in an electron microscope and corresponds generally to the one illustrated and described in the above-mentioned copending application Ser. No. 648,623.

The device comprises a winding 1 preferably but not necessarily made of superconducting material. The magnetic flux produced by the winding when energized is shielded away from the centrally located electron-optical axis of the lens device. This is done with the aid of two tubular shielding cylinders 2 and 3 which consist of superconductor material and are in heat-conducting connection with a cyrogenic medium C, such as liquid helium or liquid air, supplied to a jacket space surrounding the coil 1. The jacket structure of heat conducting metal is joined with the respective foot portion of the shielding cylinders 2 and 3 by heat-conducting metal cover discs. The two cylinders 2 and 3 are coaxially spaced from each other along and in coaxial relation to the lens axis z thus defining a lens gap s between the mutually opposite end faces 6 and 7 of the cylinders. Each end face is bevelled along its periphery so as to be approximately matched to the configuration of the magnetic field lines in the lens gap s.

The use of superconductor materials in such lens devices is useful because the aperture error of the lens device, which affects the attainable resolving power, can be reduced by increasing the magnetic field strength in the lens field region of the corpuscular beam and by decreasing the length of this region With the conventional electromagnetic lenses, operating at normal room temperatures and equipped with iron yokes and pole shoes, these requirements cannot be met to an extent sufficient for high resolution because of the magnetic properties of the iron. This is due to the fact that the production of high magnetic field strengths in the region of the corpuscular beam requires large iron cross sections to avoid saturation phenomena, thus increasing the axial length of the region in which the lens field acts upon the beam. Superconducting materials, however, afford attaining considerably higher magnetic field strengths without appreciable increase in the length of the range within which the lens field acts upon the beam.

The aperture error constant C_o, aside from being dependent upon the maximum field strength H_o in the lens gap, is also determined by the field gradient along the axis in the lens gap. Assuming, for explanation, that the field is at least approximately barrel shaped, the magnitude of the field gradient for a given maximum value H_o of field intensity in the gap is determined by the so-called half width magnitude $2d$ of the maximum field intensity. This magnitude, significant to the invention, will be explained presently with reference to FIG. 2.

In the coordinate diagram of FIG. 2 there are plotted along the abscissa z the magnitudes d, while the ordinate indicates the ratio of the field strength H to its maximum value H_o. The half-intensity width $2d$ is defined as the field width at H/H_o= 0.5. This width is entered in the graph of FIG. 2 by a straight horizontal line located at H/H_o=0.5 and having a horizontal length corresponding to the half-intensity width $2d$.

As mentioned, the requirement for minimizing the axial extent of the region in which the lens field acts upon the beam, makes it important to minimize the half-intensity width $2d$. Heretofore it has been thought that the magnitude of $2d$ depends upon the gap width s, the shape of the mutually opposed end faces of the two cylinders that define the gap s, and the wall thickness of the shielding cylinders. The wall thickness is denoted by w in FIG. 1, although it should be understood that FIG. 1 mainly serves as an example of the invention and that the wall thickness need not be uniform in each cylinder and that the wall thickness of one cylinder may also differ from that of the other.

Predicated upon the concept just mentioned, it has been proposed according to FIG. 1 of the above-mentioned copending application Ser. No. 648,623 to adapt the shape of the mutually opposed end faces approximately to the configuration of the field lines; and with a suitably chosen gap length s, the wall thickness w of the shielding cylinders has been so chosen as to prevent the magnetic field from appreciably penetrating into the cylinders.

The present invention takes advantage of the discovery that the half-intensity width $2d$, commencing from a minimum value, is virtually independent of the wall thickness of the shielding cylinders; and this is the fundamental reason this is the fundamental the feature of the present invention according to which, in a magnetic lens device generally of the above-described type and as exemplified in FIG. 1, the shielding cylinders 2, 3 in their respective end portions 2*a*, 3*a* adjacent to the mutually opposite end faces 6, 7 at the lens gap consist of a superconductor material of higher current-carrying capacity than that of the other portions 2*b*, 3*b* of the shielding cylinders. This takes into account the recognition that it is permissable if the magnetic lens flux penetrates into the shielding cylinders at least in the region of their jacket surfaces, as long as the magnetic flux remains prevented from penetrating into the immediate proximity of the corpuscular beam itself, excepting only the lens gap wherein the lens effect of the field is to be utilized and concentrated.

By virtue of having the magnetic field enter into the jacket region of the cylindrical shielding structures, instabilities otherwise apt to result from excessively high critical current densities, are minimized or obviated. However, it is essential for a defined limitation of the half-intensity width $2d$, that the magnetic flux enter as little as possible into the front face regions of the shielding cylinders because a penetration at these gap-adjacent regions may produce an effective gap width appreciably larger than the intended structural gap width s and therefore may impair the imaging qualities of the lens device.

The differentiation between high current-carrying capacity in the superconducting material adjacent to the lens gap and elsewhere in each of the shielding bodies is particularly advantageous, with respect to avoidance of instabilities due to flux jumps, if the shape of the mutually opposite front faces of the cylinders is substantially matched to the configuration of the field lines.

The above-mentioned discovery that the wall thickness of the shielding cylinders is to a large extent without influence upon the half-intensity width $2d$, is exemplified by the coordinate diagram of measuring values illustrated in FIG. 3. Plotted along the abscissa is the ratio of maximal field intensity H_o to external field strength H_a. The ordinate indicates values of the half-intensity width $2d$. The curves shown relate to respectively different parameters. The full-line curves apply to constant wall thickness W of 1.4 mm., 2.2 mm., and 3 mm., respectively. The horizontal broken lines apply to constant gap widths of 2 mm., 3 mm., 4 mm., 5 mm., and 6 mm. respectively. The broken horizontal straight lines, therefore, permit a conclusion as to the effect of changes in wall thickness w, whereas the full-line curves are indicative of changes in gap width s. For each of the straight lines the wall thickness w was kept constant; and for each of the curves the gap width s was kept constant. The indicated numerical values resulted from sample tests made in an electrolytic trough. Tests made in a different way or with different devices result in different numeral values but do not affect the conclusion—essential to the present invention, and apparent from the horizontal lines for different constant gap widths s in FIG. 3—that a change in wall thickness w does not appreciably change the magnitude $2d$ here of interest.

The field configuration in the lens device is exemplified diagrammatically in FIG. 4*a* and 4*b*. These illustrations are also based on test results made in an electrolytic trough. The superconducting cylinders were simulated by insulating cylinders **10, 11, 12, 13** which had central recesses in the respective gap-forming front faces. The opposite end face of each cylinder was provided with an electrode **14, 15, 16** or **17**. The phenomena to be studied were simulated by electric voltages between the electrodes, for example at 10 volts, and by the electric fields produced by these voltages. The lens bores are simulated by the recesses in the mutually opposite front faces of the cylinders **10, 11** and of the cylinders **12, 13**.

In the test assembly shown in FIG. 4*a* the front faces are not matched to the course of the field lines; and it will be recognized that the spreading of the field into the lens gap is impeded as compared with the front face configuration according to FIG. 4*b* where the end faces have a rounded, generally convex shape substantially matched to the course of the field lines. Furthermore, in the cylinder pair according to FIG. 4*a* the peripheral edges of the front faces which are located in the range of high field strength, are danger points for the occurrence of flux jumps which may result in asymmetries such as astigmatism. Such danger is eliminated by virtue of the front face configuration shown in FIG. 4*b*. The illustrations further show that the field strength at the front faces, especially where the beam passes through the cylinder bores, is considerably lower than the cylinder jacket. This is essential in view of the fact that according to the invention that front face portions have a particularly high shielding action, since at these localities the resulting field configuration does not cause the occurrence of high critical shielding current intensities which, at the high shielding current densities involved, might readily lead to instabilities.

In a lens device according to the invention the occurrence of field penetration at the end face regions only, can be prevented by producing these portions of a more fine grandular superconducting starting material than the other portions into which the field is permitted to more or less penetrate without impairing the imaging quality of the lens. The fine granular superconducting material in the end face portion consists for example of Nb_3Sn in form of a fine powder, whereas the residual portion (**2*b*, 3*b*** in FIG. **1**) of the lens device is made of a more compact material such as Nb_3Sn in the form of a granular material of coarser constitution than the power used for producing the front face portions **2*a*, 3*a***.

According to the invention such shielding cylinders for or in the lens devices can be produced in different ways. One of them is as follows.

A press mold for producing the shielding cylinders is filled with respective layers of superconducting granular material, the grain size of the material in the layer for the end face portion being different from the grain size of the material in the other portion of each cylinder, in accordance with the high current-carrying capacity required for the end face portions as compared with the lower current-carrying capacity in the other portion. Preferably the material for the front face portion is entered into the mold as a fine granular powder, preferably of Nb_3Sn; and the same material but of a courser constitution is used in the other portion of the shielding cylinder. After thus placing the different materials into the mold, they are conjointly subjected to pressure and temperature treatment in order to bond all of the granules together by fusing or sintering. In the lens device made with shielding cylinders produced in this manner, the corpuscular beam is shielded from the lens field with the exception of the short and narrow region within the lens gap.

Another method of producing a device according to the invention is to compose all regions of the shielding cylinders of only one kind of superconductor starting material. For example, this material may be used in granular constitution of a single average grain size, and the material placed into the mold is then compacted by pressure and heat to form a solid body in which all of the granules are bonded together. With such a molding method, care must be taken subsequently to produce in the material of the front face portion sufficient lattice defects that increase the current-carrying capacity. Such lattice defects can be produced by subjecting the front face portion of the molded workpiece to high energy radiation such as by slow neutrons. Preferably this method is preformed by first completing the shaping and solidifying of the shielding cylinders from uniform superconductive starting material, and subsequently subjecting only the front face portions that are to form the lens gap between each other to irradiation with high energy subatomic particles.

Relative to the latter method, reference may be had to a paper by H. J. Bode and K. Wohlleben in "Physics Letters, 24A," 1967, page 25, according to which the shielding properties, for example of an Nb_3Sn superconductor, can be modified in the desired sense by irradiation, for example with high energy deuterons and protons, at given particle flow quantities.

It is advisable, when producing the device with the aid of the second last described, to adjust the radiation so as to secure a substantially radial symmetrical irradiation gradient at which the region of the lens bore receives the radiation of the highest intensity. This affords placing the highest critical current intensity into the vicinity of the beam passage bore of the shielding cylinder where the magnetic field and consequently the tendency of flux jumps is already greatly decreased as compared with other localities. As a consequence, and on account of the negligible penetration of the field at the critical current density maximum, the effective shape of the lens bore and of the lens gap can virtually correspond to the one most desired for constructional or other reasons.

Still another method of producing the shielding cylinders in or for a device according to the invention is to form the shielding cylinders from a superconducting material and to alloy fissionable material into the material of the front face portion of the workpiece. After thus shaping and, if necessary, compacting and otherwise finishing the cylinders, the alloyed front face portions are subjected to radiation by slow neutrons. Suitable as such an alloying addition is uranium 235, for example (Journal of Applied Physics, Vol. 37, 1966, page 2,218.) However, other fissionable elements or mixtures, such as isotope mixtures, may be also employed in this manner. These materials, when subjected to irradiation, likewise produce lattice defects which increase the current-carrying capacity in the thin alloyed layer adjacent to the front face. It has been found that the layer thickness of superconducting material alloyed with fissionable material in the just-described manner may amount approximately to 0.1 mm., up to 1 mm. or to some larger thickness preferably in the order of magnitude of 1 mm. Irradiation may be effected, for example, in a nuclear reactor.

FIG 5 illustrates by way of example a shielding cylinder suitable as component of a device according to FIG. 1 and produced by sintering of Nb_3Sn powder applied in respectively different grain sizes as described above. The front face portion **20**, adjacent to the gap and having a front face shaped in adaptation in the field configuration, is made of a more finely granular material than the remaining portion **21** of the cylinder. As a result, a penetration of the field into the shielding cylinder in the immediate vicinity of the gap, and consequently an increase in the half-intensity width $2d$, is virtually obviated, whereas the field may penetrate into the portion **21** of the cylinder, of course not to such an extent that it may also enter into the beam passage bore **22** and thereby affect the beam.

The inhomogeneity of the shielding cylinders in a lens device according to the invention does not interfere with adapting the lens device to other requirements or desiderata. Thus, additional field-producing lens windings may be provided in the lens gap, or stigmator coils or coils for adjusting the beam within the lens may also be mounted at or in the lens gap. Furthermore, disc-shaped shielding structures may be provided at the respective other ends of the shielding cylinders remote from the lens gap, such a shielding effect being produced, for example, by the disc-shaped structures that connect the shielding cylinders **2** and **3** in FIG. 1 with the container for the cryogenic medium C.

Preferably, the invention is applicable to electromagnetic objective lens devices for electron microscopes, but is also advantageous for other lenses and for use with other corpuscular ray apparatus, such as ion microscopes or diffraction apparatus, wherever it is desirable to have the lens field act upon the corpuscular beam at a highest attainable field strength within a short distance along the beam direction.

To those skilled in the art it will be obvious upon a study of this disclosure that our invention permits of various other modifications and may be given embodiments other than illustrated and described herein, without departing from the essential features of our invention and within the scope of the claims annexed hereto.

We claim:

1. A magnetic lends device for corpuscular ray apparatus to operate under vacuum, a pair of tubular shielding cylinders of superconductive material coaxially surrounding the lens axis and spaced from each other along said axis, cryogenic means thermally connected with said cylinders, lens winding means surrounding said cylinders for generating a magnetic field, said cylinders terminating in a pair of end faces directed toward each other and other a lens gap between each other a lens gap in which said cylinders concentrate said field near said axis, in combination with the improvement according to which said shielding cylinders comprise respective end portions having a higher superconductance than the remaining portion of said respective cylinders, said end faces at said lens gap being formed by said respective end portions.

2. In a lens device according to claim **1**, said end portions consisting of superconductive material of higher current-carrying capacity than said remaining portions.

3. In a lens device according to claim **2**, said end faces of said end portions of the higher current-carrying capacity having a generally convex shape corresponding to the configuration of the lens field lines at said gap.

4. In a lens device according to claim **2**, said end portions being made of more finely granular superconductor material than said other portions of said cylinders.

5. In a lens device according to claim **2**, said end portion and said other portion of each of said cylinders being made of the same superconductor starting material, and said end portion having conductivity-increasing lattice defects in said material to thereby exhibit said higher current-carrying capacity.

6. In a lens device according to claim **1**, said shielding cylinders consisting substantially of Nb_3Sn.