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J. L. Balladore
Laboratoire d'Optique Eletronique du C.N.R.S.

R. Murillo
Laboratoire d'Optique Eletronique du C.N.R.S

J. Trinquier
Laboratoire d'Optique Eletronique du C.N.R.S

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VARIOUS ATTEMPTS TO REDUCE THE DIMENSIONS OF MAGNETIC ELECTRON LENSES USED FOR HIGH VOLTAGE MICROSCOPES

J.L. Balladore*, R. Murillo, J. Trinquier

Laboratoire d'Optique Electronique du C.N.R.S.
B.P. 4347 - 31055 Toulouse cedex, France
Laboratoire conventionné à l'Université Paul Sabatier

Abstract

Magnetic fields are used in electron microscopy for a variety of purposes : image formation, energy analysis and correction of astigmatism, for example.

We are interested in the problems of designing short focal length lenses to be used for focusing high energy electrons in the energy range 1-3 MeV.

These lenses are generally very large and we have tried to reduce their dimensions to simplify their construction and use. From this point of view, it is necessary to diminish the magnetic coil and the magnetic circuit iron.

Several solutions have been proposed in the case of the coil. We have obtained good results with superconducting coils.

The reduction of the magnetic circuit is more difficult when we try to use a smaller volume of iron ; we find that for high values of magnetizing current iron saturation appears. And we can observe a deterioration of the electron optical characteristics.

These problems can be solved by using a special magnetic circuit composed of elements of anisotropic magnetic material. These new types of lenses will be invaluable if we need to focus electrons with energies greater than 3 MeV and could lead to considerable simplification of the mechanical design of all high voltage instruments.

KEY WORDS : Magnetic lens, Electron optical characteristics, Superconducting coil, Anisotropic magnetic circuit.

*Address for correspondence:
For reprints and other information please contact J.L. Balladore at the above address. Phone no.: (61) 52 65 96.

Introduction

In very high tension electron microscopy, lenses of short focal length are needed to focus electrons with energies between 1 and 3 MeV. The chromatic and spherical aberration coefficients of these lenses should be small in order to obtain good images. Generally such lenses are very large and create difficulties in construction and use. We present here various techniques developed in our laboratory for reducing the dimensions of these lenses.

Conventional lenses

In order to focus electrons with energies in the MeV range, the maximum field on the lens axis must lie between 2 and 3 T. Such lenses have been realized in our laboratory and give excellent results (Dupouy et al. 1970, Jouffrey et al. 1979). Nevertheless their size increases rapidly as the accelerating voltage is raised. As an example, Fig. 1 shows a meridional section through the objective lenses of the 1 MeV and 3 MeV Toulouse microscopes.

In order to decrease the total bulk we might reduce the dimensions of the gap and consequently the dimensions of the magnetizing coil. If the magnetic field is concentrated in a more reduced space, for a given number of Ampere turns NI, the maximum value B_M of B becomes higher as the dimensions of the gap are made smaller. The increase of B_M obtained by reducing the gap is limited for high values of NI by iron saturation.

In Fig. 2 we present curves giving B_M at the center of the gap as a function of NI for various values of the bore diameter D of the pole pieces and of the gap width S.

We observe, for a given NI, that as S and D decrease B_M increases. This result allows us to obtain smaller focal lengths f and chromatic C_c and spherical C_s aberration coefficients, as shown in Figs. 3, 4 and 5. These values are obtained for an accelerating voltage of 1 MV.

For example, for a focal length of 10 mm, 9600 At are necessary if S = D = 8 mm and 20,000 At if S = D = 20 mm. Consequently if S and D are small we can diminish the size of the magnetizing coil.

However, modern electron microscopes are expected to provide information of many kinds about

List of symbols

B	magnetic field on the lens axis
B_M	maximum value of B
NI	number of Ampere turns
D	bore diameter of pole pieces
s	gap width
f	focal length
C_c	chromatic aberration coefficient
C_s	spherical aberration coefficient
μ_t	magnetic permeability tangent to a given curve
At	Ampere turns

the object. It is therefore necessary to accommodate specimen stages, allowing us to tilt the specimen, to modify its temperature, or to exert a mechanical constraint on it. Such devices are relatively cumbersome and since they are placed at the center of the gap the volume available between the pole pieces cannot be much reduced. In very high tension electron microscopes, the problem is complicated by the large diameter of the lenses : the specimen lies far from the outside of the microscope. The specimen stages must be relatively large in order to avoid mechanical vibrations, which occur when the object is placed at the tip of a long specimen holder.

The dimensions of the objective lens are thus severely conditioned by the nature of the experiments that we want to carry out. Under these conditions, in order to reduce the lens size it is necessary to make the magnetizing coil smaller while maintaining the number of Ampère turns needed to obtain short focal lengths with different gap volumes.

Reduction of the size of the coil

Several solutions have been proposed whereby the intensity in the current coil is increased in order to reduce the number of windings.

We mention the works of Mulvey and colleagues (Mulvey and Newman 1972) who use very efficient water cooling and have achieved an appreciable reduction of the lens dimensions.

However, the most spectacular results have been obtained with superconducting coils : Fernandez-Moran 1965, Laberrigue et al. 1976, Dietrich 1978 and Balladore 1972 have shown the advantages of using superconducting coils. For example in order to obtain 20,000 At the superconducting coil cross-section is equal to 2 cm^2. The coil cross-section on Fig. 1 a is approximately 10 times greater. Although this coil is much smaller than a conventional one the superconducting wires must of course be held at liquid helium temperature : a cryostat is therefore required.

Such methods enable us to reduce the size of the magnetizing coil, and hence the dimensions of the magnetic circuit surrounding the coil.

It is however possible to go much further in the reduction of the iron circuit.

Reduction of the magnetic circuit

The reduction of the magnetic circuit is more difficult : when we try to use a smaller volume of iron we find that for high values of the magnetizing current, iron saturation appears : the curve representing the magnetic field variations spreads along the lens axis z'z as shown in Fig.6.

These curves correspond to the lens presented in Fig. 1b. This broadening leads to a deterioration of the electron optical characteristics. On Fig. 7 can be seen the variations of the focal length as a function of NI.

We observe that as NI increases, f begins to decrease, passes through a minimum and then increases. This phenomenom is mainly due to the iron saturation. The other optical characteristics, the chromatic and spherical aberration coefficients, vary similarly. When NI is increased, therefore, magnetic saturation of the circuit appears which in turn leads to deterioration of the optical characteristics of the lens (Liebmann and Grad 1951, Murillo and Balladore 1974). In order to avoid such a deterioration, it is very interesting to know the state of saturation of the different parts of the circuit. In order to establish this, we utilize a computer method of Munro (1973) which yields the value of the magnetic field at any point of a lens with symmetry of revolution. We present in Fig. 8a the results obtained for the magnetic circuit of the superconducting lens. This figure represents one quarter of the circuit. In Fig. 8b we have drawn the flux lines.

The magnetization is equal to 31,500 A turns. For such a value the iron begins to be saturated. We have plotted the values of the magnetic field in Tesla. As we can see, the metal is not uniformly permeated by the magnetic field. Although the field distribution is practically uniform near the polepieces, it is by no means uniform farther inside the circuit. The magnetic field is concentrated in some zones along the line D, for example, the field drops from 1.63 to 0.83 T. The flux lines take the shortest path and almost all avoid part of the magnetic circuit. This basic result has been confirmed with other lenses.

In order to avoid this it is necessary to constrain the magnetic field to occupy all the iron cross-section uniformly. The aim is not to minimize saturation effects as such but to minimize the size and weight of the lens under the constraint that the magnetic flux density nowhere exceeds some given tolerable limit.

For this, we have proposed channelling the field lines by using the phenomenon of magnetic anisotropy (Balladore and Murillo 1977 ; Balladore et al. 1981). For example, let us consider a magnetic material having a magnetic permeability μ_t in the direction tangent at all points to the curve Γ, that is very much greater than the permeability in the direction δ_n perpendicular to Γ(Fig.9).

If the flux lines enter the material along μ_t their direction cannot in practice alter : they follow the preferential direction Γ. If the field is uniform along Δ_o, the same will be true along Δ_i by virtue of the anisotropy.

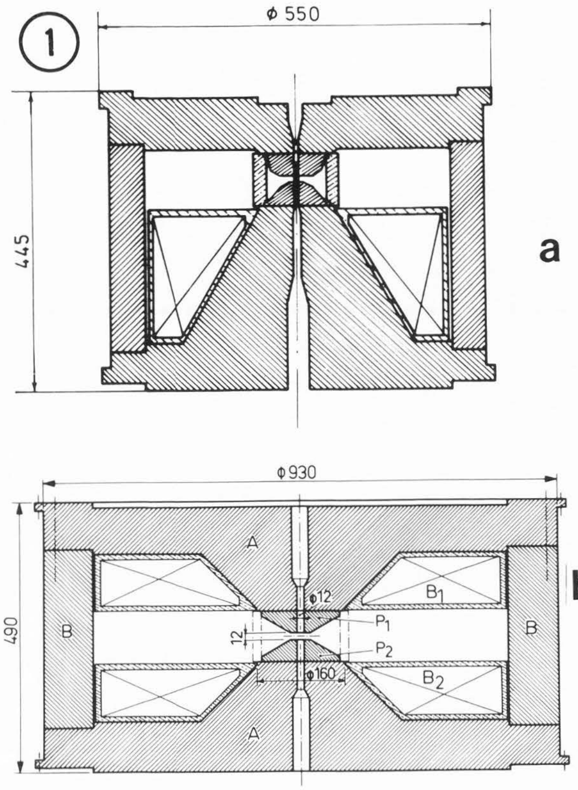


Fig. 1. a) 1 MeV objective lens
b) 3 MeV objective lens.

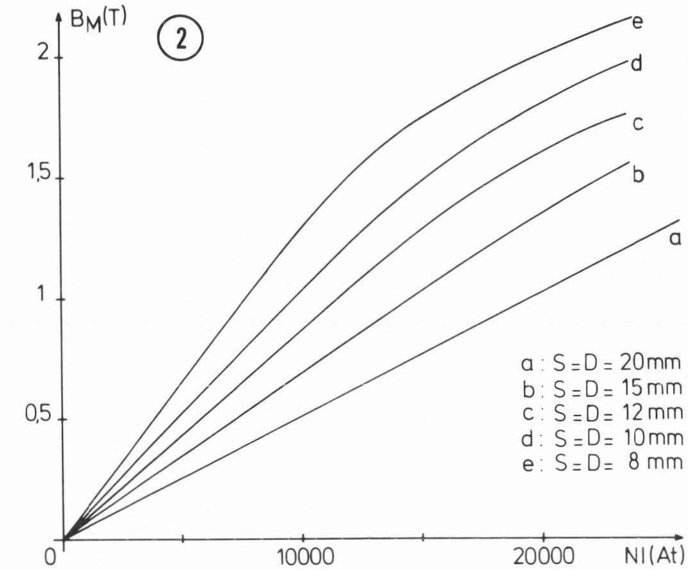
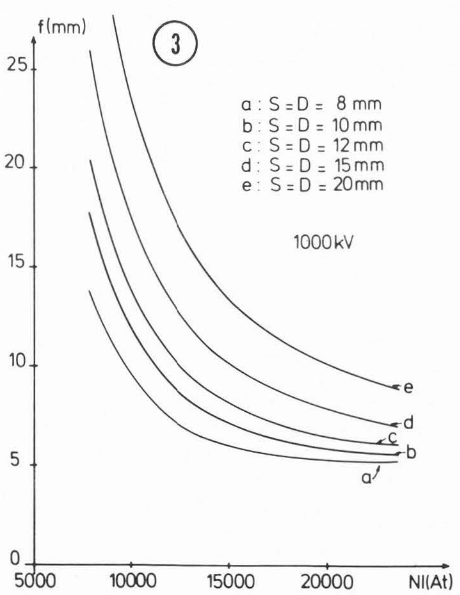
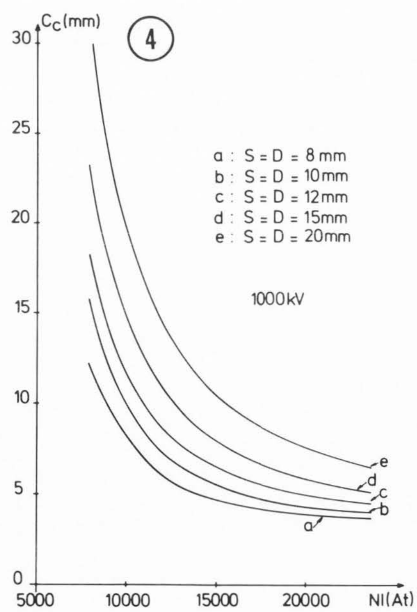


Fig. 2. Values of B_M as a function of NI for various bore diameters D of the pole pieces and of the gap width S.





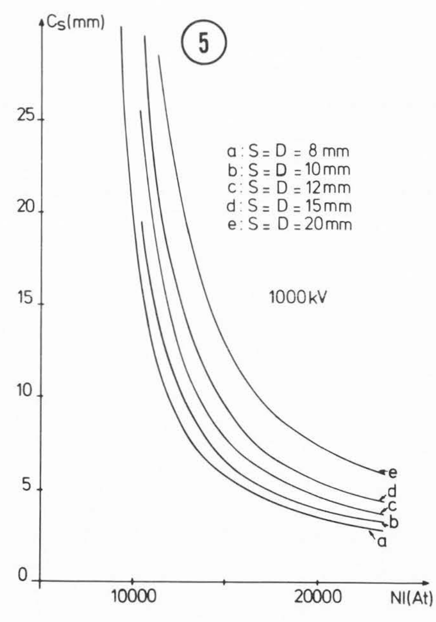


Fig. 3. Variations of the focal length f.

Fig. 4. Variations of the chromatic coefficient C_c.

Fig. 5. Variations of the spherical coefficient C_s.

	A			B		
NI (A.t)	B_M(T)	f(mm)	C_c(mm)	B_M(T)	f(mm)	C_c(mm)
7518	1.109	11.9	10.6	1.120	12	11
9941	1.451	7.6	6.4	1.458	7.5	6.3
12516	1.751	5.8	4.6	1.825	5.5	4.4
15035	1.907	5.3	4.1	2.080	4.8	3.7
17946	2.014	5.1	3.8	2.260	4.4	3.3
20034	2.099	5.2	3.6	2.390	4.3	3.2

Table 1. Optical characteristics of an experimental lens (A) and a conventional lens (B).

In order to realize such a circuit, we have simulated a magnetic anisotropic domain by making two rotationally symmetric cuts in the circuit of Fig. 8. The extremities of these cuts are in regions where the field is as uniform as possible (Fig. 10).

We have in fact two air gaps. The magnetic resistance due to these air gaps in a plane perpendicular to Γ created anisotropy : the flux lines confined to one of the metallic sections are prevented by the air gap from shifting to neighbouring sections. We note that along the line D, the field gradient is practically equal to zero. The magnetization is equal to 31,500 A turns. In the upper region of the circuit of Fig. 8, the field varies from 0.82 to 0.20 T when we go from point A to B. We see on Fig. 10 that this variation is now from 1.69 to 0.79 T between the same points : the upper part of the circuit now contributes to the flux conduction as well as the lower region. Although the volume has fallen by 30%, the computation of the maximum field on the lens axis shows that it is practically unchanged (1.947 T instead of 1.968 T).

New type of magnetic lens

A particularly small lens can therefore be constructed if discrete elements of anisotropic material having a constant cross sectional area are placed around the axis z'z. Under these conditions we have shown (Balladore et al. 1981) that the entire circuit outside the polepieces will be in the same magnetic state and there will be no region that is incompletely used by the flux lines. All the regions which do not contribute to flux conduction are excluded. Consequently this new circuit uses the minimum metal for a given maximum induction.

In Fig. 11, we present a lens designed according to these principles. The circuit is composed of two parts : two polepieces in "Hyperm 0" iron identical with those used in high voltage microscopy ; around these polepieces we have arranged eight anisotropic multilayered elements ; the number and geometry of these can be varied according to the polepiece shape and maximum field. We utilize sheets of an iron-silicon alloy with oriented grains. The magnetic permeability of this material is very much higher in the direction parallel to the sheet than in the perpendicular directions. We attempt to set these circuit end faces in a region where the polepieces are not saturated and where the field is as homogeneous as possible. The field lines enter along the direction of highest permeability and cannot shift to the next foil.

In this lens the magnetic coil consists of 1900 turns of copper wire. A very efficient water cooling is used. We can obtain 23,000 At. at a water temperature equal to 70°C.

We have determined the optical characteristics of this lens for an electron accelerating voltage of 1 MV. The values obtained are plotted in table 1. Part A represents the experimental lens (Fig. 11) and part B the normal objective lens (Fig. 1a). The values are of the same order of magnitude.

In conclusion, we can say that this magnetic circuit is very interesting for electron lenses because it enables us to reduce the dimensions of the magnetic circuit without saturation setting in. At the present time the problem that remains unsolved is the determination of the magnetic field at any point of an anisotropic circuit. The computer method used for isotropic material must be modified to take into account the anistropy. This is a far from easy problem on which we are currently working.

Conclusion

In high voltage electron microscopes, the conventional lenses that are employed are very large. The problem of reducing their volume can be solved by using superconducting or water-cooled coils and an anisotropic magnetic circuit. These new types of lenses will be invaluable if we need to focus electrons with energies greater than 3 MeV and could lead to considerable simplification of the mechanical design of all high-voltage instruments, at the cost of some loss in radiation shielding. A reduction in the total weight of the lens by a factor of the order of three should be attainable.

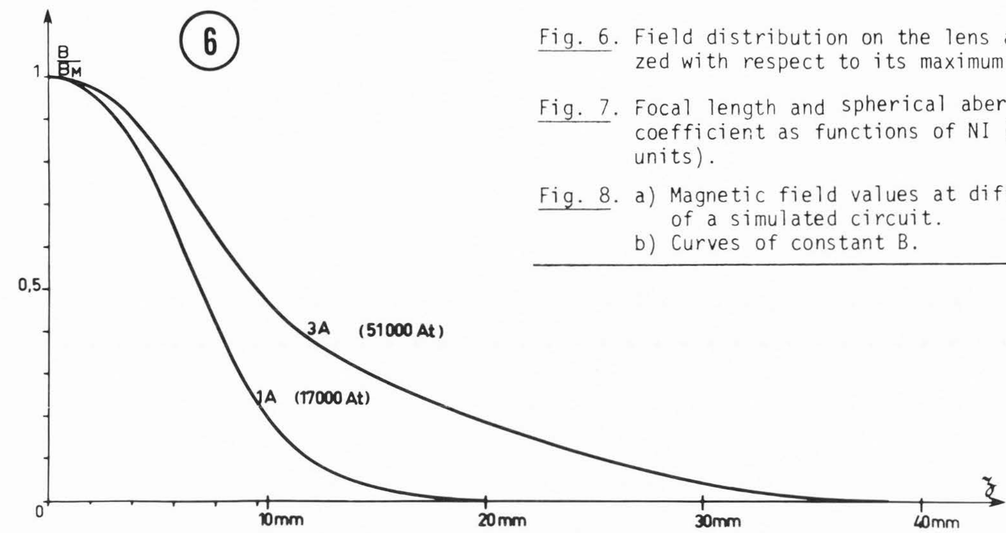
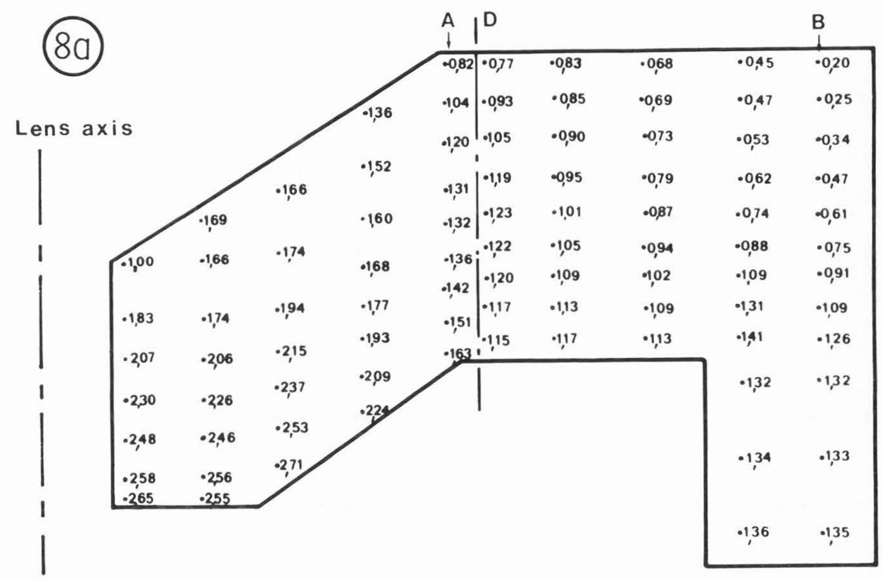
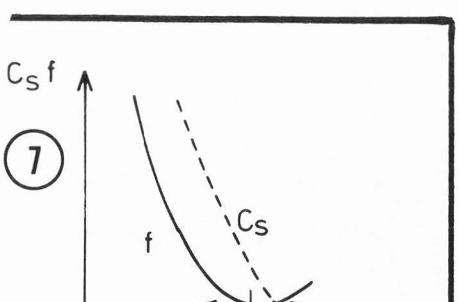


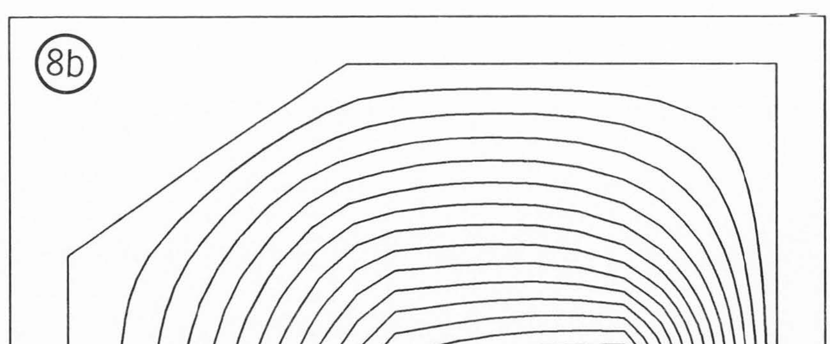
Fig. 6. Field distribution on the lens axis normalized with respect to its maximum value B_M.

Fig. 7. Focal length and spherical aberration coefficient as functions of NI (arbitrary units).

Fig. 8. a) Magnetic field values at different points of a simulated circuit.
b) Curves of constant B.







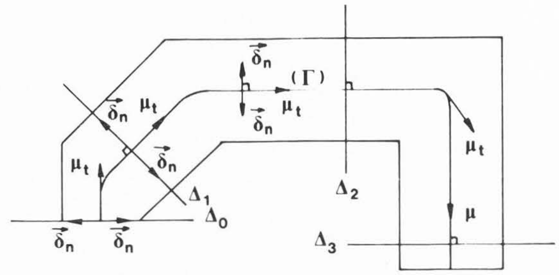
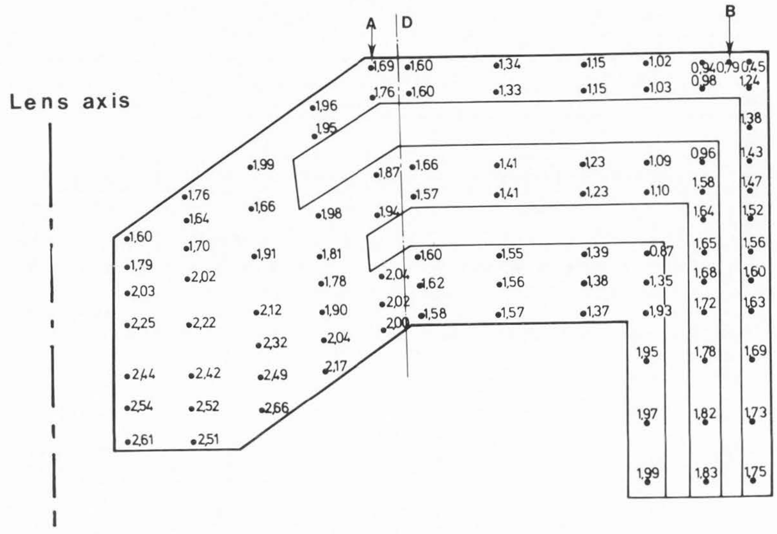
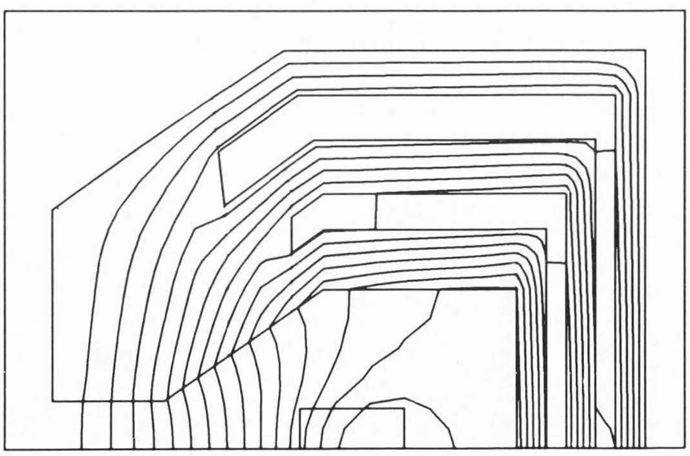


Fig. 9. Anisotropic circuit.



a



b

Fig. 10. Simulation of an anisotropic circuit

a) Magnetic field values at different points of a simulated circuit

b) Direction of the flux density B.

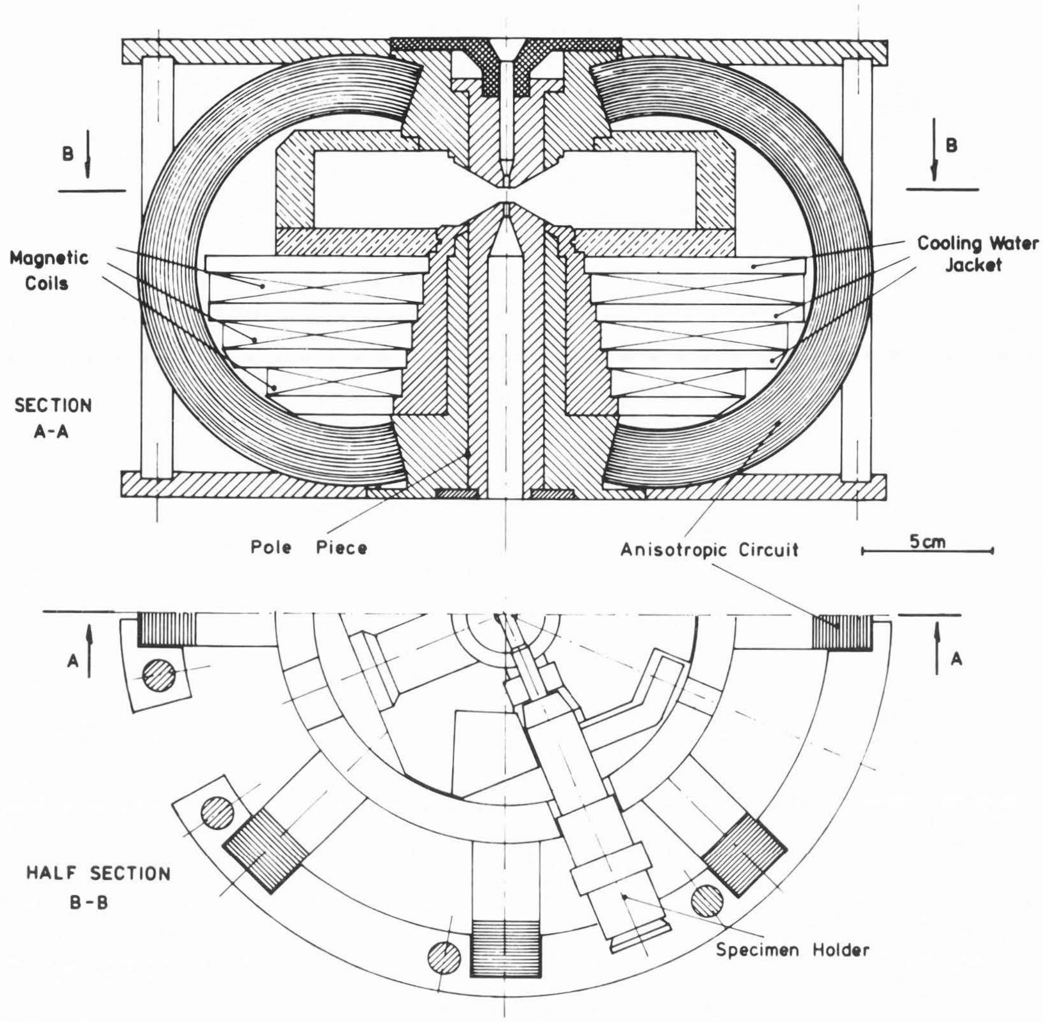


Fig. 11. New type of magnetic lens.

References

Balladore JL. (1972). Propriétés et applications des lentilles électroniques à enroulement supraconducteur, thèse Toulouse France.

Balladore JL, Murillo R. (1977). Nouveau type de lentille magnétique pour microscope électronique, J. Micro. Spectr. électr. 2, 211-222.

Balladore JL, Murillo R, Hawkes PW, Trinquier J, Jouffrey B. (1981). Magnetic electron lenses for high voltage microscopes, Nucl. Inst. and Methods 187,209-215.

Dietrich I. (1978). Superconducting lenses, 9th Intl. Congr. on Electr. Micr., Canadian Microscopical Society, Toronto 2, 173-184.

Dupouy G, Perrier F, Durrieu L. (1970). Microscope électronique 3 millions de Volts, J. Micro. 9, 575-592.

Fernandez-Moran M. (1965). Electron microscopy with high field superconducting solenoid lenses, Proc. Nat. Acad. Sci. USA 53, 2, 445-454.

Jouffrey B, Trinquier J, Balladore JL. (1979). Double focus electron probe forming lens for STEM. J. Micr. Spect. electr. 4, 89-93.

Laberrigue A, Balossier G, Genotel D, Homo JC. (1976). Développement et amélioration d'un microscope 400 kV à lentilles supraconductrices, 6th Europ. Congr. on Electr. Microsc. Tal Publishing Co., Jerusalem 1, 338-339.

Liebmann G, Grad EM. (1951). Imaging properties of a series of magnetic electron lenses, Proc. Phys. Soc. B, 54, 956-971.

Mulvey T, Newman CD. (1972). Versatile miniature electron lenses, 5th Europ.Congr. on Elect. Micr. Manchester, The Inst. of Physics, London, 116-117.

Munro E. (1973). Computer-aided-design methods in electron optics, Thesis Cambridge, England.

Murillo R, Balladore JL. (1974). Etude des éléments cardinaux d'un objectif à pièces polaires saturées, J. Micr. 20, 1-14.