High Current Density Magnetic Electron Lenses in Modern Electron Microscopes

J. Podbrdský
Institute of Scientific Instruments

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HIGH CURRENT DENSITY MAGNETIC ELECTRON LENSES
IN MODERN ELECTRON MICROSCOPES

J. Podbrdsky
Institute of Scientific Instruments, Brno, Czechoslovakia

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Abstract

New possibilities for the application of high current density magnetic electron lenses in commercially produced electron microscopes are discussed. The optimum current density in the windings of a commercially produced instrument has been determined. An improved indirect water cooling arrangement with a closed, vibration-free, cooling circuit has been found to be a reliable and practical system. This has been made possible by a substantial improvement in the method of manufacturing wire coils, leading to a greatly increased heat transfer. The reduced dimensions of such coils have made it possible to design a general purpose lens body, that is readily adapted to the various imaging modes required in practice. The optical properties of a new combined condenser-objective-diffraction lens, exploiting the best features of conventional and non-conventional lenses, allows one to achieve new imaging modes, e.g. low-angle selected area diffraction or combined convergent-beam electron diffraction and high resolution imaging. This compact but complex lens unit requires microprocessor control of the lenses to ensure rapid and convenient transfer between the various imaging modes that are available. Fortunately systems for implementing this are now currently available.

Introduction

The trend of development of transmission electron microscopes in the last two decades, e.g., the increase in accelerating voltage and resolving power, the requirements of reduced aberrations and the inclusion of both TEM and STEM methods in one instrument lead to the conclusion that the optical system of such an instrument can work properly only if the number of lenses is increased considerably. The practically attainable resolution is limited not only by the lens properties but also by the thermal and mechanical stability of the instrument. The space taken up by the excitation coils, and hence the length of the microscope column, becomes a limiting factor for electron microscope design. It was quite natural therefore that in the seventies the concept of "mini-lenses" should appear, based on the idea that in principle the current density in an effectively cooled copper winding can be increased by one or two orders of magnitude compared with the generally accepted value. The term "mini-lens" is frequently used for any magnetic electron lens in which the current density is substantially greater than the normal value of about one Ampere per square millimeter. Moreover, a substantially reduced cross-section of the exciting coil creates the necessary conditions for the design of special classes of unconventional lenses (cf. Mulvey 1982).

Depending on the specific arrangement of the magnetic circuit, three typical groups of unconventional lenses may be distinguished in the literature of the last fifteen years:
1) Iron-free lenses (see Mulvey 1982 pp376-384).
2) Magnet-free lenses.
3) Superconducting lenses.

The basic limitation of classical lenses is the saturation of the polepieces of the magnetic circuit. Values of the magnetic field exceeding some 2-2.5 T can be reached either by using special magnetic materials at liquid helium temperatures or by using iron-free lenses. The current density normally attained in the conventional form of copper windings does not allow the necessary concentration of amper-turns in a small volume, whilst the use of superconducting materials causes troubles with the necessary insulation of the exciting coil. The magnetic field on the optical axis in such lenses is determined by the shape of the exciting coil; accordingly we can speak of cylindrical, helical,
conical and other lenses. In theory, iron-free lenses can reach lower aberration coefficients than those of polepiece lenses, but in practice it is very difficult to obtain the necessary constructional precision of the exciting coil compared with that achievable in a magnetic polepiece. The absence of magnetic materials, however, increases the number of ampere turns required for a given focal length and at the same time increases the sensitivity of the axial field distribution to asymmetries in the exciting coil and in any magnetic materials in the vicinity.

b) Single polepiece lenses (Mulvey and Newman 1973, 1974, Munro 1973) are magnetic lenses with extremely asymmetric axial field distributions caused by the particular shape of the coil and the magnetic circuit itself. The axial magnetic field distribution, in the region where the magnetic circuit is open, approximates to an exponentially decreasing field; in the closed part of the iron circuit, the field decreases much more rapidly. One of the advantages of such "open lenses" is that they can be placed outside the vacuum chamber and still produce a high flux density at the required object position inside the vacuum. For example, the final lens of a scanning electron microscope or the magnetic cathode lens of a high brightness field emission gun may be separated from the high vacuum in this way (Smith and Swann 1969). Furthermore, the unusual distortion aberrations of these lenses, namely high aberration in one orientation and low aberration in the other can be exploited to realise a wide-angle distortion-free projector system (Elkamali and Mulvey 1980). On the other hand, a single polepiece lens cannot reach as short a focal length, and hence as small a chromatic or spherical aberration as that of a double polepiece lens. In general, therefore, single polepiece lenses are not likely to be used as objectives in very high resolution microscopes but could well find an area of application in analytical microscopes where a large free solid angle is required around the specimen for electron and X-ray detectors of various types.

c) Magnetic lenses with conventional magnetic circuits but with dimensions that are minimised by the employment of high current-density coils have optical properties that are comparable to those of conventional lenses. However, their small axial extent allows multiple lens combinations that would be excluded by a conventional magnetic circuit. Examples of this would be rotation-free doublets (Mulvey and Newman 1974, Juma and Mulvey 1978, Podbrdsky 1981) for projector systems or those auxiliary lenses which must be placed extremely close to another lens, e.g., the "twin lens" concept introduced by Philips for TEM/STEM objective lenses. Increased current density in conventional lenses is also important in high voltage electron microscopy where the standard current density has led to an economically unacceptable increase of lens, and hence column, dimensions.

If we disregard purely experimental instruments, the mini-lenses of type c have found the greatest field of commercial production for lines and STEMs. In some cases "quasi-single polepiece lenses" of type b are beginning to appear, since in the case of extreme asymmetry, the double polepiece lens merges imperceptibly into the domain of the single polepiece lens.

The theoretical and experimental results mentioned above give the designer a greatly extended freedom for improving the design of magnetic lenses within the existing framework of the CTEM. This may be illustrated by a practical example if we recall that in a 120kV TEM the maximum excitation of any lens coil in the column need rarely exceed 5000 Ampere-turns. An objective lens may sometimes need more, but usually two coils are provided in objective lenses. With a current density of 500A/mm², the cross-section of a wire coil with a filling factor of 0.6 is only 130mm² and could be reduced to 10-15 mm² by exploiting the boiling water cooling system, and incorporating a tape winding with a filling factor of 0.9. Taking into account the dimensions of the magnetic circuit as well as the necessary space for the cooling system and the electrical connections, we readily conclude that such extremely high values of current density are not advantageous for conventional electron microscopes although they may be useful for special applications. A reasonable value of the current density must take into account the required size reduction of magnetic lenses. This must then be reconciled with the increased power required in the winding and with the increased demands on the cooling system. Clearly these must not counteract the benefits brought about by the reduction in the
High current density electron lenses

![Diagram](image)

- a) Typical magnetic circuits for a conventional electron lens.
- b) With axial length reduction, the central core of the lens may be removed.
- c) With short polepieces and no central core, the volume of the coil can be reduced.

The input power \( W \) needed to support an excitation of \( NI \) A-turns in a coil of rectangular cross-section, as shown in Fig. 1, is given by:

\[
W = \frac{\pi \rho (D_2 + D_1)(NI)^2}{(D_2 - D_1)} 1 \lambda
\]  

(1)

where \( \rho \) is the specific resistance of the winding, and \( \lambda \) is the filling factor. If several lenses are to be placed in a limited space along the optical axis, reducing the axial length is preferable to reducing the outer diameter as illustrated in Fig. 1b. The power required is inversely proportional to the axial length of the coil, but by shortening the coil, the diameter of the central core of the lens can be substantially reduced (Podbrdsky 1984), as illustrated in Fig. 1c. This means that the inner diameter \( D_1 \) of the coil can also be reduced. If \( D_2 < D_1 \), Equation 1 takes on the simplified form:

\[
W = \frac{\pi \rho (NI)^2}{1 \lambda}
\]  

(2)

In conventional lenses, the current density does not usually exceed some 1-3 A/mm². For excitations of 1,000-10,000 A-turns, the coil cross-section is in the range of 10-50 cm², leading to column diameters in the range 200-300 mm and axial lengths of the lens body of 100-250 mm. If the axial length of the coil is reduced to 10-20 mm, the power necessary for an excitation of 5,000 A-turns is around 90-180 kW (cf. Eq. 2 with \( f = 0.9 \)) for a winding and around 130-260 kW (\( f = 0.6 \)) for a winding with a round wire. The current density \( \sigma \) is given by:

\[
\sigma = \frac{2NI}{(D_2 - D_1)} 1 \lambda
\]  

(3)

or if \( D_2 < D_1 \),

\[
\sigma = \frac{2NI}{D_2} 1 \lambda
\]  

(3a)

In most cases, it is not necessary to reduce substantially the outside diameter; a reasonable value for \( D_2 \) is about 80-100 mm. The value of \( \sigma \) is then between 10 and 20 A/mm², according to Eq. 2.

The inner diameter of the coil can be substantially reduced in the way shown in Figure 1 only in the condenser or projector lens. The more complicated design of the objective lens with its associated mechanical stage and specimen manipulating mechanisms, aperture holder etc. does not usually allow one to place the coil in the center of the lens gap. In practice, therefore, the \( D_1 / D_2 \) ratio is about 2-4 and the dimensions of the objective lens coils are correspondingly greater than those of the projector and condenser lenses. Consequently, the current density in an objective coil would typically be 10 A/mm² and the optimal axial coil length some 20 to 30 mm.

The third group of lenses that has made its appearance in electron microscopes of the last decade is that of auxiliary lenses, used especially for the optimization of objective lenses in various operational modes of TEM and STEM. Their outer diameter must be reduced to a value that enables them to be placed inside the objective polepieces themselves. The relatively low excitation required (1,000-2,000 A-turns), together with their small dimensions, leads to a higher optimum current density, 20-50 A/mm². The corresponding range of power needed is about 30-100 kW.

**Choice of the proper cooling system**

From the point of view of current density and heat transfer between coil and coolant, all the systems mentioned above are sufficient for medium current densities. Unfortunately, almost all the published results concerning the cooling of high current density coils do not discuss two questions that are important for the successful commercial realization of mini-lenses. These are the technological difficulties encountered in producing the unconventional coil and its subsequent long-term reliability.
Wire windings are easy to manufacture since insulated copper wire is produced in a wide range of diameters and suitable winding machinery is available. Copper tape is not always readily available in the dimensions needed to match convenient power supplies. Experience suggests that tape windings are not advantageous for current densities below 50A/mm² and their larger filling factor does not prove to be of over-riding importance in the face of the other difficulties.

Many experiments by the author have shown that it is very difficult, if not impossible, to reach really long-term reliability with direct water cooling of insulated copper wire. Sooner or later, the electrically insulating properties of all coils tested became unacceptably low. The use of de-ionised cooling water does of course help considerably, but in practice this is extremely difficult to maintain. If the maximum heat transfer from coil to coolant does not exceed 2-3W/cm², it is more promising to use indirect cooling of the coil faces by a water-cooled disc, insulated from the coil surface by a thin Mylar sheet. This method of cooling can be almost as effective as direct cooling for the current densities under consideration. In any case, it turns out that the heat transfer from the inside of the coil to the outside is a more important factor here. Our experiments were therefore orientated to the solution of this problem, namely how to increase the heat transfer between the turns of a wire coil. If this can be achieved, it would then be feasible to cool the coil from one side only, thereby greatly simplifying the construction of the cooling system.

Experimental results

In order to illustrate these ideas, the maximum temperature was measured in a coil of dimensions D₁=25mm, D₂=90mm, l=15mm, and cooled from one side only, as shown, for example, in the lens coil in Figure 3. The temperature distribution in the region of the coil and the
were inserted between each layer of turns instead which is readily measurable in our design. We was wound with 820 turns of 0.6mm insulated copper grease. Nevertheless the impregnation still plays T₂ in the coil was not appreciably affected by grease at this interface. With these new maximum temperature for a given power consumption depends essentially on the average coefficient of disc. The temperature increase T₂ across the coil is determined by the smoothness of the coil surface and the thickness(around 20 μm) of the insulating Mylar foil and on the average thermal conductivity of this region. In the region of the coil itself, the average axial distribution of temperature is nearly parabolic with a maximum at the thermally insulated "hot" side far removed from the cooling disc. The temperature increase T₂ across the coil depends essentially on the average coefficient of thermal conductivity of the coil. Both T₁ and T₂ are, of course, linearly dependent on the total power generated in the coil. The coil in question was wound with 820 turns of 0.6mm insulated copper wire. Such a coil of 8 Ohmas resistance at room temperature needs a power of 187 W for an excitation of 4000A-tums (4.8A,39V). It is not possible to measure the internal temperature distribution in the coil. Fortunately, however, the maximum admissible excitation is limited solely by the highest temperature in the coil, which is readily measurable in our design. We therefore measured the surface temperature of the "hot" side of the coil for different cooling arrangements, as a function of the power supplied to the coil; the results are shown in Fig.2b. The maximum admissible power for the coil with a conventional winding was found to be about 100 W (2500 A-t) only, since the surface temperature reached some 120-130°C, as shown in curve (A) of Fig.2b. After impregnating the coil and coil-cooling-plate with silicone grease, the temperature rise was less for a given power (curve B) thereby allowing the power to be increased to 130 W, (3000 A-t.). At constant temperature, the power consumption increases as the square of the excitation; in fact it increased more rapidly than this because of the substantial increase of the average coil temperature and hence its resistance. It seemed therefore difficult to make substantial improvements to the heat transfer in conventional windings. It then occurred to the author that a substantial improvement of the axial conductivity in the axial direction might be possible if a layer of copper tape, of some 60μm thickness, were inserted between each layer of turns instead of the thin paper sheets used in standard commercial winding practice. This idea proved to be an immediate success and greatly reduced the maximum temperature for a given power consumption in the coil. At the same time, the thermal contact between the coil end face and the cooling disc was improved by introducing a thin layer of silicone grease at this interface. With these new constructional methods, the maximum temperature in the coil was less than 60°C even at an input power of 190 W (4000A-t) as shown in curve (C). The enhanced thermal conductivity provided by the copper tapes is so good that the temperature rise T₂ in the coil was not appreciably affected by subsequent impregnation of the winding by silicone grease. Nevertheless the impregnation still plays an important role at the coil-disc interface, where the thermal drop can well reach a value of 20-25°C at high input powers and even more if the surfaces are in poor mechanical contact. The effect of inadequate thermal contact is shown in curve (D) of Fig.2b, where silicone grease is absent but other experimental conditions, e.g. copper interleaving sheets, were maintained. It should also be mentioned that this new construction results in a remarkably rigid coil, even in the absence of any epoxy resin or other binding material. This also helps in maintaining a a smooth, regular coil surface at the interface with the cooling plate. These results are consistent with the more detailed calculations obtained by the author from a computer model of the coil and cooling plate system. However, an experimental check of the theory with a specially constructed coil equipped with an array of thermocouples has not yet been completed.

A coil with "single-side" cooling must be thermally insulated from the lens casing on the "hot" side. In order to reduce heat transfer between the coil and the lens body a thin sheet of felt (D) was attached to the outside of the coil. The water flow through the cooling disc was adjusted so that the temperature difference between input and output is about 3°C, the cooling water temperature was stabilised at a value slightly higher than room temperature.

High current density electron lenses

These reliably-cooled coils, capable of being produced commercially, gave a sound basis for the design of an experimental electron-optical system (Podbrdsky 1984) with a wide range of possibilities. Three basic magnetic lenses were designed as universal elements of illuminating and projector systems. These are illustrated in Figure 3. The magnetic circuit of the double polepiece, rotation-free lens (Fig.3A) consists of three iron parts a,b,c and two excitation coils e. Without additional polepieces it works as a rotation-free intermediate lens. By inserting additional polepieces in one or other of the bores, the optical properties can be adapted to those of a final projector lens with low spiral distortion. The magnetic circuit of lens 3B differs only slightly from that of lens 3A; the greater separation between the two lens gaps makes it possible to use the doublet as two independent lenses. The optical properties can, of course, be varied by a suitable design of the removable polepieces p. Finally, for applications where compensation of image rotation is not necessary, for example, in the illuminating system, a single lens of the same shape as those shown in Figs.3A,8 has been designed (Fig.3C). An excitation of 4000A-turns is available in this lens for a power consumption of about 100W. In the double lens, each section requires 180W for its contribution of 4000A-turns. The optical properties of the individual elements of this set of lenses are determined essentially by the design of their Practical design of high current density lenses.
pole pieces and hence are indistinguishable from those of classical lenses. The chief difference is that entirely new lens systems are possible with them since radically new layouts of the combined elements are possible.

The new symmetrical condenser objective, shown in Figure 4, consists of three parts. The design of the upper (a) and lower (c) sections containing the excitation coils (d) is similar to that of the excitation coils of condenser and projector lenses. An excitation of 12,000 A-turns is attainable with an input power of $2 \times 300$ W. The single-side cooling discs operate at a flow rate of 2x1.2 litre/min, at a water pressure difference of about 3-5 kPa. The middle section (b) carries the specimen stage and aperture holder and can be adapted for various analytical purposes. The exchangeable pole pieces (p) can be designed with small bores and gaps for high resolution or alternatively with large dimensions for easy specimen handling, but with some loss of resolving power. Both pole pieces contain auxiliary lenses (m) whose mid-planes are located at a distance of 50 mm from the centre of the condenser-objective lens, as shown in Figure 4. This distance is sufficiently large to allow two pairs of deflecting or centering coils (f) to be placed between the mini-lenses and the objective lens field but is substantially smaller than the normal distance (around 120-130 mm) that is possible with conventional lenses. The excitation of the mini-lenses (up to 2000 A-turns) gives a minimum focal length of about 15 mm. By making full use of the mini-lenses, the optical parameters of the condenser-objective lens can be accurately adjusted for a broad spectrum of operating modes.

A condenser-objective lens equipped with two auxiliary lenses is a complex optical system but has many operational advantages over the original Riecke-Ruska design. Its optical parameters are determined not only by the excitation of the individual lens components but quite critically by the position of the specimen in the objective lens gap. The reason for this is that the optical parameters of the three-lens system...
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system is divided by the specimen plane into two distinct regions, the illuminating region and the imaging region. The illuminating part comprises the upper auxiliary lens and the objective pre-field; the imaging part comprises the objective imaging field and the lower auxiliary lens. The optical system, therefore, consists not of three lenses but of four. These will be referred to, not quite exactly, as second and third condenser lens (C2, C3), objective lens (OL) and diffraction lens (DL). The basic imaging mode is shown schematically in Figure 5a. The objective lens images the specimen SP into the object plane (II) of the projector system. Suppose that the position of the specimen in the condenser-objective lens field is chosen so as to enable a sufficiently small aperture of the illuminating beam to be achieved. In our case it means that the specimen is not too near the plane of symmetry. If the angular aperture is sufficiently small, i.e. less than 10⁻⁴ radian, the diffraction pattern appears in the objective focal plane OA. In the absence of a special

diffraction lens this pattern can be imaged on the final screen only by moving the object plane II of the projector system into the plane OA. The focal parameters of the intermediate lens must therefore be changed and the magnification of the diffraction pattern on the fluorescent screen will be relatively small. The auxiliary lens in the lower polepiece, however, which is substantially nearer to the diffraction pattern plane can be used as a diffraction lens imaging the plane OA into the projector object plane II without changing any parameters of the projector system (Fig.5b); the range of operation of the diffraction mode may thus be considerably increased (Podbrdský 1982). Another application of the diffraction lens is in the low magnification mode. With the objective lens switched off, the image in the object plane II of the projector is formed by the auxiliary lens (Fig.5c).

From the point of view of the imaging system, the specimen position in the magnetic field influences the parameters of the objective lens only marginally and causes only small differences in the objective focal length and aberration coefficients. The proper choice of the optimum object position for the required imaging mode must be made with respect to the optical parameters of the pre-field and the attainable parameters of the illuminating system. The second condenser lens together with the objective pre-field C3 form the optical system whose optical parameters are given by the optical parameters of both C2 and C3. While the focal length of C2 can be chosen independently, the optical properties of C3 are explicitly given by the specimen position. For each specimen position, the objective lens excitation is determined by the requirement that the image of the object should be more or less at infinity. The effective focal length of the system C2-C3, which depends on the specimen position and on the focal length \( f_2 \) of the second condenser lens, is shown in Figure 6. This figure shows contours of constant focal length as the specimen position \( Z \) and focal length \( f_2 \) are varied. These curves were calculated numerically for a lens gap width of 0mm. The object position was varied from the highest possible value \( Z = -4 \text{mm} \) when the influence of the pre-field is negligible, through the central position \( Z = 0 \) of the Riecke-Ruska lens, and then through the second-zone Suzuki position \( Z = 1.2 \text{mm} \), where the pre-field itself acts as a telefocal system. Of course, not all these positions are of practical importance. The properties of the auxiliary lens in its role as a second condenser are analogous to those of a standard lens but the reduced distance between condenser lens and specimen improves its working conditions and allows a better adjustment of the illuminating beam parameters to the various working modes. Nevertheless it is not possible to reach all working modes purely with the aid of the second condenser lens at a given optimum specimen position. Extremely different requirements include, for example, an illuminating aperture of less than 10⁻⁴ radian for specialised electron diffraction or interference microscopy. Alternatively, a probe diameter in the sub-nanometer region may be required for STEM or a
probe with an angular aperture of $10^{-2}$ radian might be needed for convergent beam micro-diffraction. These requirements can only be reached by changing the axial position of the specimen. Some instruments solve this problem by providing a Z movement for the specimen (Suzuki et al. 1984). The 4-lens system described above may provide an electron optical analogy of axial specimen shifting by means of the auxiliary diffraction lens. The ray diagram of this method is shown in Figure 7b.

For standard high resolution imaging the specimen is placed slightly above the mid-plane of the objective lens. The illuminating beam is focussed into the specimen plane by the second condenser lens as shown in Figure 7a. The diffraction lens is switched off in this operation. If the condenser lens forms a parallel beam, it is concentrated by the objective pre-field into a very small spot below the specimen. In order to bring the spot into the specimen plane, the excitation of the objective must be increased (Fig. 7b). The specimen will then be no longer imaged into the plane II but into the plane II' between the objective and the diffraction lens. By means of the diffraction lens, the plane II' can be focussed into the plane II so that at the fluorescent screen a focused image of the specimen will appear illuminated by an extremely small spot with a high angular aperture. By changing the excitation of the diffraction lens, the diffraction pattern which is formed in the back focal plane OA of the objective lens may be focussed onto the final screen (Fig. 7c). In both cases the imaging conditions are sufficient for reaching a very good resolution. This procedure allows one to change imaging modes between the HREM image and the CBED pattern without changing the axial position of the specimen. In this way, details of interest in the image can be recognised at the highest resolution and immediately verified by convergent beam diffraction or some other analytical technique.

**Microprocessor Control**

In order to achieve all the working modes described above, a simultaneous change of excitation of all three lenses is required. For example, if it is necessary to re-focus the image, as a result of axial drift on the part of the specimen, it is desirable to keep the illuminating beam parameters unchanged by correcting the excitation of C, and to compensate the change in final image magnification or rotation by means of the diffraction lens. The great variety of possible working modes requires the use of microprocessor technique. In view of the broad spectrum of low-cost microprocessor control systems available it is advantageous to use de-centralised control with a special microprocessor system designed for every function block. This solution is particularly advantageous for the above three-lens system, where not only is simultaneous lens control necessary but moreover the control of the alignment system is also difficult. The limited space for deflector coils and stigmators in the objective polepieces means that the same coils must be used for lens
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alignment and beam tilt and deflection in the specimen plane. The settings of the deflection system depend however on the optical strength of the objective prefield. Taking into account the wide variety of conditions to be met in the different working modes, it becomes clear that the use of microprocessor control of the above lens system is not merely a question of operator convenience; it is a necessary condition for achieving optimum results.

Conclusions

The advantageous properties of mini-lenses have been recognised for ten years and have been used in numerous TEM, SEM, high voltage HREM and analytical microscopes. However, most of the applications were in experimental instruments or by modifying existing instruments. In the commercial field, mini-lenses have been used only as auxiliary lenses with substantially smaller excitations than those of the main lenses of the instrument. The reason is probably the more complex technology necessary for the production of mini-lenses with a long-term reliability comparable to that of conventional lenses, a factor that is not so important in experimental equipment. The commercially available TEMs, STEMs and SEMs work very satisfactorily with conventional lenses so can the effort to optimise multi-lens systems be justified?

If the present trend of combining transmission, scanning, diffraction and analytical methods in one instrument continues, the answer to this question is yes since in such an instrument a large number of lenses are required. In order to keep the length of such an instrument within reasonable limits the axial length of the coils must be substantially reduced. In addition, by adopting a unified lens construction as set out in this paper, it would be possible to manufacture commercially a series of specialised instruments for particular purposes based on the universal set of miniature lenses described here.

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References


Discussion with Reviewers

Reviewer I: Has sufficient experience yet been obtained to give confidence in the lifetime and reliability of the silicone grease impregnated coils (see "Experimental results")? Have problems
been experienced with localised heating at voids or irregularities in the windings?

Author: In the experimental system, nine miniature coils have been in operation for about a year without a single failure. The basic idea behind this design is to average out the temperature gradient in the coil by means of thermally conducting sheets placed between the layers of the winding. This virtually eliminates any danger of local over-heating of the coil.

Reviewer I: In the system shown in Fig.4, has it been possible to achieve satisfactory symmetry of the iron-free coils and their alignment with respect to the main polepieces? Have criteria been established for these tolerances?

Author: The technology of producing the auxiliary lenses in the objective polepieces is indeed complicated but nevertheless perfectly feasible. Both iron-free and polepiece mini-lenses have been tested. We have found it possible to achieve a constructional precision of about 0.01mm; however this does not guarantee perfect alignment. For precise alignment, deflecting coils and stigmators seem essential.

E. Munro: In a high resolution electron microscope, do the large temperature changes in the magnetic lenses arising from the high power dissipation in your miniaturised coils, cause any practical problems, such as the microscope drifting out of alignment or the specimen position drifting? Does the rapid flow of cooling water give rise to any vibration problems?

Author: On the one hand, the temperature of the lens body is stabilised by the cooling disc which is in contact with it. On the other, the heat transfer from the coil to the lens body is minimised by means of the thermal insulation, which is not shown in fig.3 (but see Figs. 2b and 4).

E. Munro: In your Fig.4 you show miniature coil windings located inside the lens bores. Could windings of this type, if energised in opposition to the main windings, be used to cancel out the stray fields that appear in the back bores of a magnetic lens when it is run under saturation conditions at a very high excitation?

Author: In principle, the miniature coil could be used for the compensation of this stray magnetic field, at least for a given excitation. As oversaturation is a non-linear effect, problems could arise in the accurate setting of such a compensation over a wide excitation range.

E. Munro: Can you please comment on the type of power supplies needed for these high-power dissipation lenses, and whether there is any difficulty in obtaining the current stability required for high-resolution microscopy, at these high power levels?

Author: These power sources are quite conventional. The output current ranges from 2 to 8A, well within the capability of standard transistors. The reference resistor must be carefully designed and thermostatically controlled. The power to be dissipated in the series transistor can be reduced by using a preliminary control of the output voltage of the power supply as a function of the desired output current.