Current and future aberration correctors for the improvement of resolution in electron microscopy

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The achievable resolution of a modern transmission electron microscope (TEM) is mainly limited by the inherent aberrations of the objective lens. Hence, one major goal over the past decade has been the development of aberration correctors to compensate the spherical aberration. Such a correction system is now available and it is possible to improve the resolution with this corrector. When high resolution in a TEM is required, one important parameter, the field of view, also has to be considered. In addition, especially for the large cameras now available, the compensation of off-axial aberrations is also an important task. A correction system to compensate the spherical aberration and the off-axial coma is under development. The next step to follow towards ultra-high resolution will be a correction system to compensate the chromatic aberration. With such a correction system, a new area will be opened for applications for which the chromatic aberration defines the achievable resolution, even if the spherical aberration is corrected. This is the case, for example, for low-voltage electron microscopy (EM) for the investigation of beam-sensitive materials, for dynamic EM or for in-situ EM.

Keywords: aberration correction; electron microscopy; high resolution; scanning transmission electron microscope; transmission electron microscope

1. Introduction

Only a few years after the invention of electron microscopy by E. Ruska, the first papers were published on the theoretical background of charged-particle optics and especially on the unavoidability of the main axial aberrations (Scherzer 1936), i.e. spherical and chromatic aberrations. This statement, however, was only valid for rotationally symmetric round lenses, for systems free of charge and for time-independent fields, and it was later called the ‘Scherzer theorem’. Scherzer (1947) proposed ways out of the dilemma of the impossibility to design an aberration-free electron objective lens. What one has to do is to deviate from one of the restrictions of the Scherzer theorem: hence, one has to use either a multipole system or a time-varying field or to place a charge at the back focal plane (or at its conjugate plane). The latter is impossible if one does not want to disturb the ray path, but the other two ways have been recognized as possibilities to correct spherical and chromatic aberrations.

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It took exactly 50 years, however, to realize a spherical aberration corrector with which the resolution of a transmission electron microscope (TEM) could be improved (Haider et al. 1998). In the course of these 50 years, a few projects to design and build correctors for the compensation of axial aberrations were started but none could be finished successfully. The first projects were carried out in Darmstadt and Tübingen, Germany (Seeliger 1951; Moellenstedt 1956), and in the 1960s an aberration correction system was built at the Cavendish Laboratories, UK (Deltrap 1964; Hardy 1967). In the 1970s, Crewe started a correction project to compensate the spherical aberration for a dedicated scanning TEM (STEM) (Crewe 1982). At about the same time, in Darmstadt, Scherzer and Rose designed an aberration correction system for the simultaneous correction of the spherical and chromatic aberrations of a TEM. For this latter project, at least the proof of principle could be demonstrated for spherical and chromatic aberrations simultaneously (Hely 1982). However, this project was also stopped in 1982 without any improvement of resolution when compensating these most disturbing aberrations. Although the final goal could not be achieved, one important result for the people involved in this project was the recognition of the feasibility of a hardware aberration corrector for high-resolution electron microscopy.

In the late 1980s, funding of a new aberration correction project was almost impossible and, therefore, a smaller project without external funding was started for the compensation of the chromatic and spherical aberrations of a low-voltage scanning electron microscope (LVSEM). This LVSEM was designed for biological studies of uncoated specimens at the European Molecular Biology Laboratory (EMBL), Heidelberg, Germany, and this project was finished successfully in 1995 (Zach & Haider 1995). Hence, this development was the first aberration correction system with which an improvement of the resolution from about 5.6 nm down to about 1.8 nm could be attained.

What was not yet solved at that time was the improvement of the highest resolution of a TEM. Rose (1990) proposed a new hexapole correction system for such an electron microscope (EM), which would allow the imaging of a fairly large object area at a resolution around 0.1 nm. Rose called it a semi-aplanat because the intrinsic anisotropic off-axial aberrations were not increased and the real part of the off-axial coma, the isotropic component, could be compensated by the transfer lenses he introduced.

In 1992, a joint project of three groups in Germany, the theory group of Rose (Darmstadt), the experimental physics group of Haider (Heidelberg) and the materials science group of Urban (Jülich), was started. They succeeded in convincing the VW-Foundation to fund this project. The proof of principle of this hexapole corrector was shown on a test-bench at an early stage of the project (Haider et al. 1995), and in 1997 the breakthrough in aberration correction for a high-resolution EM was announced by Haider at the 1997 Dreiländertagung in Regensburg (Haider et al. 1997).

About 5 years later, the first commercially available systems for high-resolution TEM came on the market. The compensation of the spherical aberration for a probe-forming system for STEM was also started in the mid-1990s and the proof of principle was demonstrated in 1997 (Krivaneck et al. 1997). The breakthrough in resolution was achieved in 2003 with a quadrupole–octupole corrector (Krivaneck et al. 2003). Since then, the compensation of spherical aberration has stimulated...
many groups to fully exploit the benefits of such improved high-resolution TEMs and STEMs, and the spherical aberration corrector is now a widely accepted new tool. Up to now, more than 100 systems have been installed worldwide and aberration correction has become an almost routinely used technique.

The first electron microscopes equipped with an aberration corrector were designed for the resolution achievable at that time and, hence, the available microscopes were not as stable as one would have liked because only the improved resolution demonstrated the limitations of the base instruments that existed in those days. Hence, the EM manufacturers recognized the need for further improvements of the overall stability of the TEM/STEM and have made large investments in new instruments with a higher intrinsic stability and instruments designed for highest resolution by means of aberration correctors.

2. Current spherical aberration correctors

(a) The hexapole corrector

The first successful development of a corrector to compensate the spherical aberration of the objective lens of a 200kV TEM was a hexapole correction system. However, the application of hexapole elements for the correction of spherical aberration requires a setup for which the strong axial second-order aberrations of the hexapole elements are cancelled while the third-order effect on $C_3$ is maintained. Two hexapole stages can be combined such that their threefold astigmatism compensates each other and the contributions with negative sign of both stages to the third-order spherical aberration add up. This step was taken by Beck (1979) and Crewe (1980). Unfortunately, these early systems suffered from axial fourth-order three-lobe aberration as pointed out by Rose (1981). This aberration prevents a useful application, even in a probe-forming microscope (STEM).

The correction system for TEM, as proposed by Rose (1990), consists of a minimum of strong elements that are two hexapoles and two round lenses to circumvent the aforementioned problem of fourth-order aberrations (figure 1). However, in order to avoid any introduction or increase of off-axial aberrations and higher-order aberrations due to combination aberrations (Uhlemann & Haider 1998), an additional transfer lens doublet is incorporated. Hence, the design of this hexapole corrector consists of two modules: an upper part with a double transfer lens and additional image deflectors and stigmators, and a lower part with two multipole stages to generate the strong hexapole fields (HP), two transfer lenses (TL) and a final adapter lens (ADL). The transfer lens doublet in the upper part is necessary to match the coma-free plane of the objective lens with that of the hexapole corrector. The coma-free plane of the objective lens is situated very close to its back focal plane; without the transfer system, off-axial third-order coma and fifth-order spherical aberration $C_5$ would be too large to achieve a substantial improvement in high resolution. This arrangement has the advantage that all second-order aberration rays vanish identically outside the corrector. Today, this system forms the basis for all available hexapole correctors.

Shortly after the first commercial system for TEM was finished, it became obvious that the hexapole corrector is also very suitable as a probe corrector in STEM. In order to improve the resolution in STEM, the illumination angle has to
be increased. This additionally provides a higher beam current for a $C_3$-corrected STEM. We named the hexapole corrector for STEM as CESCOR (where the S stands for STEM). From 2001 to 2003, the first commercial hexapole corrector for STEM was developed for a JEOL 2010F (S)TEM. This system, finally installed at Oxford University, is shown in figure 2 (Hutchison et al. 2005). It was the first double-corrected (S)TEM equipped with two hexapole correctors: one in the illumination system and the other in the imaging system. With this system, high-resolution TEM imaging can be combined with the analytical capabilities offered by a $C_3$-corrected STEM (Sawada et al. 2005).

The precise Zemlin tableau technique based on the analysis of diffractograms could not be used for aberration measurement for a STEM $C_3$ corrector. Diffractograms of STEM images do not provide the same information as for conventional TEM (CTEM) images. We finally implemented a combination of the tableau technique with an analysis of the STEM point-spread function. The latter
method was originally developed for the LVSEM corrector by Zach & Haider (1995). To analyse the aberrations of the probe-forming system, the illuminating beam is tilted between the gun and the corrector and the point-spread function is deconvoluted from STEM images in overfocus, Gaussian focus and underfocus. Then defocus and twofold astigmatism are calculated from the shape of the point-spread function. The evaluation of the tableau afterwards uses the same methods as those used for CTEM.

For the CTEM hexapole corrector, two transfer lenses are used in front of the first hexapole element. For STEM, a transfer system between the lower hexapole and the objective lens is also necessary to avoid the strong fifth-order spherical aberration $C_5$ as a combination aberration. To avoid scan coma in STEM, additionally, the scan unit must be placed between the corrector and the objective lens. This could be achieved by using a single transfer lens or, preferentially, by using the most often available condenser mini-lens close to the objective lens in addition to a further transfer lens to maintain flexibility when adjusting the correction strength for different high voltages. Over the years, hexapole correctors have been adapted to several objective lenses with different pole pieces. However, the preferential choice is still a high-resolution small-gap
pole piece with small $C_3$ and $C_c$. This system has minimum chromatic focus spread and small fifth-order residual intrinsic aberrations. With the advent of commercially available correctors, most TEM manufacturers started to redesign their columns by concentrating more on the overall mechanical and electrical stability. Zeiss, for example, introduced a hanging column for their high-resolution TEM (Essers et al. 2002) and FEI developed the Titan 80-300 series (Van der Stam et al. 2005).

(b) The advanced hexapole corrector

In 2004, the Transmission Electron Aberration-corrected Microscope (TEAM) Project (TEAM 2005) set the goal of 50 pm resolution in STEM and TEM. To achieve this ambitious goal in STEM, the residual phase shifts for large aperture angles of at least 40 mrad must be controlled. This requirement made a partial redesign of the conventional hexapole corrector and, therefore, the development of an advanced hexapole corrector, a so-called D-COR, necessary.

For the D-COR, special care had been taken to reduce the intrinsic sixfold astigmatism $A_5$ introduced by the corrector and to offer the possibility to compensate for the fourth-order parasitic aberrations by appropriate alignment tools (Müller et al. 2006; Hartel et al. 2007). This was possible because our understanding of the detailed mechanisms of how the intrinsic combination aberrations and residual parasitic aberrations are produced in the system had improved substantially over the years. By design, we reduced the coefficient of the intrinsic sixfold astigmatism $A_5$ by more than one order of magnitude from 2–3 mm down to below 200 μm (Hartel et al. 2007). Additionally, by tuning the transfer lenses between objective lens and corrector, the coefficient of the intrinsic fifth-order spherical aberration $C_5$ can be corrected (Hartel et al. 2004).

To obtain the finally achievable STEM probe size, the results must be convoluted with the shape of the geometrical image of the virtual source at the specimen plane. The calculations listed in table 1 compare two systems: a reduced-gap 200 kV objective lens with small $C_3$ and small $C_c$ and a standard-gap 300 kV objective lens. With a Schottky-type field emission gun (FEG) with $\Delta E = 0.7$ eV (full width at half-maximum, FWHM), both systems are limited by chromatic focus spread (Haider et al. 2000) and not by fifth-order aberrations. If the energy width is reduced to $\Delta E = 0.3$ eV (FWHM), the aperture angle can be increased accordingly. For a CESCOR-type design, the sixfold astigmatism now becomes the limiting aberration for both systems. In this regime, the advanced D-COR-type design is most appropriate and can be used to push the STEM $d_{50}$ probe size down to 50 pm and to increase the probe current without loss of spatial resolution for an acceleration voltage of 200 or 300 kV.

Therefore, the D-COR design further pushed the limits for STEM resolution. The Ronchigram shown in figure 3 shows a phase-flat area of 60 mrad. With the first prototype installed at CEOS, Heidelberg, in a standard FEI Titan 80-300, we were able to demonstrate 0.082 nm dumbbell resolution in an image of Ge in 211 orientation at 300 kV (figure 4) (Hartel et al. 2007). In the diffractogram (not shown), the reflections for the 426 directions also are visible corresponding to a lattice spacing of 78 pm. With the final TEAM 0.5 instrument equipped with a D-COR, the 0.063 nm Ga dumbbells of GaN in 211 orientation have been resolved with clear reflections in the diffractogram corresponding to 0.049 nm
Table 1. List of achievable diameters for various illumination cones and different energy lengths. For the diameter of the calculated electron probe, different criteria can be used such as $d_{\text{FWHM}}$, $d_{30}$, $d_{50}$ and $d_{59}$. The $d_{30}$, $d_{50}$ and $d_{59}$ indicate that 30, 50 or 59 per cent of the beam current is confined within this diameter. The $d_{59}$ corresponds to the Rayleigh criterion.

<table>
<thead>
<tr>
<th>figure</th>
<th>$\alpha$ (mrad)</th>
<th>$\Delta E \ast C_c$ (eV mm)</th>
<th>$d_{\text{FWHM}}$ (pm)</th>
<th>$d_{30}$ (pm)</th>
<th>$d_{50}$ (pm)</th>
<th>$d_{59}$ (pm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5a</td>
<td>25</td>
<td>0.7 $\ast$ 2.4</td>
<td>46.2</td>
<td>41.3</td>
<td>63.0</td>
<td>75.3</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>0.7 $\ast$ 2.4</td>
<td>39.6</td>
<td>42.7</td>
<td>69.7</td>
<td>87.0</td>
</tr>
<tr>
<td>5b</td>
<td>40</td>
<td>0.7 $\ast$ 2.4</td>
<td>36.1</td>
<td>47.5</td>
<td>81.4</td>
<td>101.3</td>
</tr>
<tr>
<td>5c</td>
<td>40</td>
<td>0.7 $\ast$ 1.2</td>
<td>33.7</td>
<td>32.8</td>
<td>50.0</td>
<td>60.7</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>0.7 $\ast$ 0.6</td>
<td>32.2</td>
<td>27.1</td>
<td>39.2</td>
<td>45.6</td>
</tr>
<tr>
<td>5d</td>
<td>40</td>
<td>0.7 $\ast$ 0.1</td>
<td>32.1</td>
<td>25.5</td>
<td>36.4</td>
<td>42.1</td>
</tr>
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Figure 3. Ronchigram of an amorphous layer with an outer border showing a semi-aperture of 80 mrad. The aberration-free area extends in this case to about 60 mrad.

for the 555 direction as shown in a publication by Kisielowski et al. (2008). Additionally, with an Au sample, a 0.048 nm reflection in the diffractogram was demonstrated. These results achieved the ambitious goal of the TEAM Project for STEM at 300 kV and, finally, set a new world record in STEM resolution (Kisielowski et al. 2008).

For easier operation, additional alignment methods were defined and implemented in software. For the D-COR, alignment tools for automatic compensation of all axial aberrations up to and including the fourth order now exist. In total, 18 real-valued aberration coefficients can be controlled during the user alignment.
3. Future correctors

(a) STEM $C_c$ corrector

As was explained in §2b, with the D-COR-type design, it is possible to use very large STEM apertures. Nevertheless, the aperture used for these systems is much smaller since the STEM $d_{50}$ probe size (i.e. the diameter of the disc that contains 50% of the total probe current) is primarily governed by the chromatic focus spread. For a standard Schottky FEG at 300 kV, the optimum aperture amounts to $\alpha = 25$ mrad. To exploit the full benefits of the advanced hexapole STEM corrector, it would be advantageous either to combine the corrector with a cold field emitter or a high-brightness Schottky FEG equipped with a gun monochromator or to combine the performance of the D-COR with $C_c$-correction capability. The latter is to compensate simultaneously within one corrector the spherical and chromatic aberrations.

For the achievable performance of lateral resolution of such a system, only the product of energy width $\Delta E$ and the chromatic aberration coefficient $C_c$ is the important parameter. The energy width of the primary beam is not affected by the chromatic aberration correction. Therefore, such a corrector would not improve the energy resolution that can be achieved with a monochromator but it would maintain the angular intensity, and with an increased aperture, one would even obtain a much higher beam current. With an energy length reduced down to 0.8 eV mm, the optimum aperture angle (for minimum $d_{50}$) would increase to $\alpha = 40$ mrad at 300 kV. The attainable STEM $d_{50}$ probe size with an assumed virtual source size of 25 nm for an illumination angle of 25 and 40 mrad and for three different energy lengths is shown in figure 5.
An electron probe $C_s/C_c$ corrector has already been developed for an LVSEM (Zach & Haider 1995) and a similar system could be used for a high-resolution STEM (figure 6). The minimal system consists of four multipole elements to generate the required strong quadrupole fields for focusing purposes and the required octupole fields for the compensation of the spherical aberration. For the correction of the chromatic aberration, the two inner elements, the $C_c$-correction elements, have to have combined electrostatic and magnetic quadrupole fields with which the chromatic aberration in the $x$–$z$ and $y$–$z$ sections can be cancelled. In order to avoid any introduction of higher-order axial aberrations, the required multipole fields have to be generated with the needed precision to avoid any parasitic axial aberration. Moreover, the requirements on the stability of the power supplies for the crossed electric and magnetic quadrupole fields are one order of magnitude higher than those for strong focusing elements because about 90 per cent of the quadrupole strength is used for the correction of $C_c$ and only the remaining 10 per cent is used for focusing properties. However, because of the independent noise of the current and voltage supplies, any small variation in one of the supplies first changes the focus in one section and does not vary the chromatic aberration coefficient of one section.
Figure 6. Aberration figures at the image plane showing the effect of the azimuthal off-axial coma. The aberration figure increases linearly with the distance from the central axis and with the square of the acceptance angle of the objective lens. The circle shows an assumed limit of the induced phase shift by $\pi/4$ if only rotational symmetric axial aberrations are present. Curve with square, $dE = 0$; curve with circle, $dE > 0$; curve with cross, $dE < 0$.

The benefits of the compensation of chromatic aberration in STEM can be best observed when investigating the electron probe shape under different parameters as listed in table 1. For this purpose, an accelerating voltage of 300 kV and a standard high-resolution pole piece have been assumed. For all calculations, the same brightness of the gun with a virtual source size (including noise) of 25 pm has been assumed. In the case of only $C_3$ correction and an aperture corresponding to an illumination angle of 25 mrad, a resolution in the sub-Ångström region can be achieved. However, going to a larger illumination cone of 40 mrad, one can obtain a small FWHM but not the more important $d_{50}$ criterion below 1 Å. If one reduces the energy length by compensating the chromatic aberration—or by using a monochromator, which would reduce the available beam current—the electron probe could be dramatically sharpened by this means. Although the FWHM is not changed much, the observable tail of the probe is strongly reduced and the electrons are pushed from the tail to the centre of the electron probe. Hence, the central height of the probe is increased and this would allow a high-density electron probe to be positioned onto a single atomic column, which would be advantageous for analytical purposes, for example.

The development of such a $C_c$-corrected ultra-high-resolution STEM is a challenging project and should not be underestimated, although such a type of corrector already exists for an LVSEM. However, the requirements with respect to precision and stability are again higher if one aims for a resolution below...
1 Å in the STEM case compared with a resolution of around 1 nm as aimed for with an LVSEM. The development of such a C₃-corrected STEM is an ongoing project.

(b) The hexapole aplanat

About 30 years ago, Beck (1979) discovered the negative spherical aberration of a hexapole doublet. Ten years later, Rose (1990) pointed out that it is essential to adapt the hexapole C₃ corrector to the objective lens by a transfer lens system, in order to make it applicable to the CTEM. The reason for the transfer system is twofold. On the one hand, it avoids a large fifth-order spherical aberration that would otherwise arise as a strong combination aberration between the objective lens and the corrector. On the other hand, the transfer lens system allows imaging of the coma-free plane of the objective lens into the coma-free plane of the corrector. The isotropic off-axial coma of the system vanishes only if this condition is met. We would call an optical system that is free of spherical aberration and off-axial coma ‘aplanatic’. However, unfortunately, the magnetic objective lens also introduces anisotropic off-axial coma that still remains even if the coma-free planes are matched. Rose suggested the term ‘semi-aplanat’ for a spherical aberration-corrected system that is free of isotropic coma and still has anisotropic off-axial coma.

Today, hexapole semi-aplanats consisting of a magnetic round lens and a hexapole doublet are commercially available options for both the TEM and the STEM operation mode of the microscope. Optimized and stable current drivers and high-voltage supplies and the increasing availability of monochromators have dramatically improved the information limit of the microscopes. Sub-Ångström resolution is now readily available, and hence apertures in the range of 25 mrad to even 40 mrad become usable. Considering these large apertures, the remaining anisotropic part of the off-axial coma seriously limits the field of view that can be imaged with some, nearly constant, phase shift. We can draw a circle of radius $R$ around a perfect corrected axial point, which indicates that an additional $\frac{\pi}{4}$ phase shift due to the off-axial coma is surpassed. Assuming a typical dimensionless coefficient of $C_{aay} = 2/3$ for the anisotropic off-axial coma, the $\frac{\pi}{4}$ radius can be illustrated as shown in figure 7. According to this criterion, only 600–2400 equally well-resolved image points can be resolved for a TEM capable of an information limit below 1 Å. Hence, one needs an advanced hexapole corrector that is also capable of eliminating the anisotropic part of the off-axial coma. Combining this corrector with a magnetic objective lens results in a true aplanatic optical system, which we will consequently call an ‘aplanat’.

A correction system capable of compensating not only the spherical aberration but also the azimuthal off-axial coma needs more multipole elements than the conventional hexapole corrector. The reason why a conventional hexapole corrector does not affect the azimuthal off-axial coma is its simple setup. In order to have a hexapole corrector free of second-order aberrations, the two hexapole fields have to be imaged exactly one to one, with also exactly the same orientation, in order to compensate each other’s induced strong threefold astigmatism of the hexapole fields. Therefore, in order to generate an azimuthal contribution of the off-axial coma within a hexapole corrector that should compensate the off-axial coma of the objective lens, one needs at least one additional hexapole field.
Figure 7. Layout of a minimal aplanatic hexapole corrector. This system only consists of three hexapole elements and two transfer lens doublets. The hexapole elements have to be oriented around the optical axis with respect to each other.

(Haider et al. 2008a). In order to generate the required azimuthal off-axial coma, the hexapole fields have to be rotated with respect to each other around the optical axis (figure 8).

Therefore, the minimal system consists of three hexapole elements and round lenses between the hexapoles. Such a minimal system is shown in figure 8. In order to eliminate all aberrations of second order, to eliminate all axial aberrations of fourth order, to compensate the spherical aberration and the azimuthal off-axial coma, this minimal system has to fulfil certain requirements with respect to the symmetry of the system and the length and strength of the hexapole fields and round lenses. Such an aplanat is currently under development and should be in operation in about 2 years time.

(c) The $C_c/C_s$ corrector for TEAM

The instrumental development for high-resolution electron microscopy was strongly stimulated by the initial development of the first applicable $C_s$-corrected 200 kV TEM about 10 years ago (Haider et al. 1998). Up to now, the objective lenses of CTEM/STEM have been optimized for high resolution by reducing the intrinsic aberrations such as spherical and chromatic. However, this was...
Improvement of resolution

Figure 8. The set-up of the quadrupoles of a $C_s/C_c$ corrector as used for an LVSEM and which, in principle, could also be used for a high-resolution probe-forming system. The axial rays are focused at the specimen plane although the energy is varied by ±10 per cent.

only possible with the consequence that other imaging modes, e.g. *in situ* or Lorentz microscopy, suffer from this optimization and no improvement for these additional imaging modes could be gained by correcting only for the spherical aberration. In addition, the accelerating voltages have been steadily increased over the years in order to gain resolving power with a shorter wavelength of the used electrons. Hence, the high-contrast regime for light atoms at lower voltages, such as 60–120 kV, is no longer used for high-resolution EM.

For a real breakthrough of electron microscopy in almost all imaging modes, the second resolution limiting aberration, i.e. chromatic aberration, has to be cancelled by a multipole corrector too. For this purpose, an initiative was taken by Gibson in 2000 and later taken over by Dahmen to form a team of several groups of DOE laboratories to set up an electron microscope aiming for the unprecedented lateral resolution of 50 pm for materials science applications (TEAM 2005). The resolving power of this new unique instrument is not the only goal that has to be tackled. First, there is also the need for a large field of view, which also requires the compensation of the off-axial coma, and second, considering all aberrations together, the ultimate aim is to achieve a so-called aberration-free imaging over the entire image. For this latter purpose, the acceptable phase shift over the whole image due to residual aberrations is just $\pi/4$. This new TEAM instrument is currently under development. The most challenging part of this instrument is a new $C_c/C_s$ corrector with precise electron optical components and very stable power supplies.

The electron-optical concept for the $C_c/C_s$ corrector has been developed in order to fulfil all the requirements for the TEAM Project. Besides the requested high resolution and large field of view, we also wanted to achieve a not too complicated corrector and the increase in length of the column should be acceptable. Rose (2004) proposed an ‘ultracorrector’ that would fulfil the required electron-optical performance but would lead to a long and complex system. Therefore, after long discussions and calculations, we decided to go for an ‘apochromat’ consisting of 10 quadrupole elements and with which we can compensate $C_s$, $C_c$ and the off-axial coma $B_3$ of the objective lens. This

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system allows an aberration-free imaging at a resolution of 50 pm at 200 and 300 kV and a very large field of view. This large field of view fully exploits the capabilities of an 8k × 8k charge-coupled device (CCD) camera up to the information limit. This ‘achroplanator’, a $C_s$-,$C_c$- and $B_3$-compensated objective lens, is optimized for high-resolution work between 80 and 300 kV. It consists of 10 quadrupole elements, octupole elements, several deflectors and round lenses to adapt the beam path and to allow the required precise alignment in order to achieve aberration-free imaging up to a spatial frequency of 20 nm$^{-1}$. Owing to this required high number of multipole elements, we need an ultra-stable power supply unit consisting of 151 current and four voltage supplies.

The prototype of this achroplanator has been designed and constructed, and it has been built into a ‘Titan’. The overall length of this C-COR (short name of the achroplanator) is more than 82 cm, and owing to the required excitation strength of the main correction elements, we had to increase the cross section of this piece of column from 30 to 35 cm (figure 9). Hence, the overall length of the Titan is increased by this additional corrector and care had to be taken for this increase in length and weight (+470 kg). Currently, this new C-COR is in operation and has already proved its capability to fully compensate the chromatic aberration of the objective lens for the main acceleration steps in the range from 80 up
Improvement of resolution

Figure 10. Measurement of the induced defocus when the energy is varied over a large range from $-1500$ to $+1500\,\text{eV}$. For a large range of energy of almost $1000\,\text{eV}$, there is no noticeable change of focus which indicates a very small $C_c$. In addition, the chromatic aberration of third rank (which depends on the square of the relative energy width) is compensated too. Circle, measurement; solid line, fourth-order fit; dashed-dotted line, theoretical prediction; steep dashed line, uncorrected case.

Figure 11. An extended Zemlin tableau of (a) an only $C_s$-corrected TEM and (b) a $C_c/C_s$-corrected TEM. In the case of the correction of $C_c$, the contrast of the Thon rings is not damped for the images taken with a tilted beam, whereas for the $C_s$-only correction this damping in the tilt direction is clearly visible. The tilt of the beam is in both cases $35\,\text{mrad}$.

to $300\,\text{kV}$. The measurement of the chromatic aberration shows almost no change of defocus even for a very large variation of energy of $1000\,\text{eV}$ as shown in figure 10.

All components are behaving as they should, and up to now, any need for a modification of a component has not been noticed. Besides the axial coherent and the chromatic aberration, also the off-axial aberrations could be measured and

\textit{Phil. Trans. R. Soc. A} (2009)
compensated to the required level. The prerequisites stated for this complicated correction system (Haider et al. 2008) could all be fulfilled. One of the important parameters that had to be fulfilled is, for example, the focus spread. The focus spread, which is caused by chromatic aberration, is strongly reduced due to the compensation of $C_c$. This can be observed by a Zemlin tableau for which, in the case of $C_c$ correction, no damping of the contrast of Thon rings at larger tilt angles can be observed (figure 11). However, what has not yet been achieved so far is the real breakthrough with the spatial resolution. The goal that we are aiming for is a resolution of $d = 50 \text{ pm}$ for 300 and 200 kV. Currently, we have achieved a resolution at 300 kV of $d = 70 \text{ pm}$ with full compensation of $C_c$ and $d = 60 \text{ pm}$ if $C_c$ is not fully compensated and approximately $C_c = 1 \text{ mm}$ is left. This improvement of resolution is attained by means of lowering the ray path within the correction system and giving up the goal of full compensation of the chromatic aberration. Although the $C_c$ is increased and no monochromator is used, the resolution is improved. Within the coming weeks, this problem has to be tackled further before this microscope is transferred to the NCEM at Berkeley, CA, USA.

4. Conclusion

The history of aberration correction started at almost the same time as the invention of the electron microscope. Since then, now more than 70 years ago, many projects in aberration correction have been started and have failed. However, since the availability of new components for electron microscopy, such as PCs and CCD cameras, the hardware aberration correction could be developed successfully. After this first achievement, this instrumental development has made substantial steps towards sub-Ångström resolution. After the first installations of these $C_s$-corrected TEMs as well as $C_s$-corrected STEMs in research laboratories, the ease of operation of these new components is one of the main reasons why these complicated instruments are widely accepted.

Up to now, the first $C_s$-corrected TEMs and STEMs have almost exclusively been applied in materials science. In this field of research, corrected EMs are most beneficial because the advantages can immediately be noticed in TEM, owing to the improved contrast and resolution, and in STEM, owing to the increased beam current and improved resolution. However, $C_s$-corrected TEMs are also advantageous for biological applications if one aims for high resolution in the 2–5 Å range owing to the improved contrast.

Sub-Ångström resolution was a long ongoing dream and was requested to tackle the most important questions in materials science by the famous physicist Feynman (1960) more than 50 years ago. With the emergence of the first applicable $C_s$ correctors, the manufacturers have taken over their task to improve the inherent stability of their high-resolution TEMs. In combination with more stable instruments, the $C_s$ correctors could show their performance, leading to the long requested sub-Ångström resolution.

After the first successful project on high-resolution EM, the goal was increased again by the TEAM Project to aim for an unprecedented resolution of $d = 50 \text{ pm}$ in TEM and STEM. This goal could only be achieved with an advanced $C_s$.
Improvement of resolution

3681

corrector that also takes care of the compensation of higher-order aberrations, such as the advanced hexapole corrector. This type of $C_s$ corrector has proved its capability by achieving the ambitious goal of TEAM in combination with a high-brightness gun and a monochromator to reduce the energy width of the electron source.

Various fields of research are making it necessary to carry on the development of new specialized correctors for additional applications such as Lorentz microscopy, cryo-microscopy, in situ microscopy, etc. Currently, three different types of corrector are under development: for high-resolution analytical purposes, a $C_c$- and $C_s$-corrected probe corrector for a TEM/STEM; an aplanatic correction system for a very large field of view; and the most challenging project, the TEAM corrector for TEM. The latter will compensate not only the spherical but also the chromatic aberration and the off-axial coma. Every component seems to be working as anticipated. The still missing ultra-high resolution of $d = 50 \text{ pm}$ should be attained in the near future. This type of corrected TEM/STEM will be the most advanced electron microscope for some time.

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Phil. Trans. R. Soc. A (2009)


