Large-Aperture STEM Hexapole Cs-Corrector

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Besides correcting the spherical aberration, hexapole-type aberration correctors produce intrinsic aberrations with 3n-fold azimuthal symmetry (n=1,2,...) due to their characteristic magnetic field structure. For the early designs the six-fold astigmatism of fifth order A₅ limited the maximum aperture size for probe-forming systems. Meanwhile, three different approaches have been realized to eliminate A₅ [1-3] and the usable diameter of the STEM condenser aperture could be increased considerably, see Table 1.

After these achievements it has been argued, that for two-hexapole and even three-hexapole correctors now the three-lobe aberration of sixth order D₆ finally limits the usable aperture size [4]. For an objective lens with a medium gap size around 5mm - which is usable for analytical applications - the π/4-phase shift limit due to this intrinsic aberration was found to be just below 40mrad aperture semi-angle. As investigated theoretically [1, 6] and verified by experiments [3, 5, 10], these advanced correctors are sufficient for modern CFEG equipped microscopes to touch also the high-resolution limit set by the chromatic aberration. Optimum probe angles [7] slightly larger than 40mrad (30-300kV) became accessible. If additional phase shifts of D₆ in the order of several π/4 are reasonably counterbalanced by lower-order aberrations of the same multiplicity, D₆ hardly limits the obtainable resolution [8, 10]. However, if the intrinsic sixth-order limitation due to D₆ can be eliminated a-priori in the optics, the experimentalist could omit the potentially misleading counterbalancing techniques [10] when using the largest apertures set by the chromatic focus spread. Moreover, the availability of electron beam monochromators demands for even larger apertures, enabling not only better xy- but also improved z-resolution [9].

Here we report the first evidence, that with a new hexapole-type corrector the three-lobe aberration of sixth order D₆ can be eliminated together with higher-order spherical aberrations, shifting the theoretical π/4-limit due to intrinsic residual aberrations to around 70mrad - without any compensation measures. First ronchigrams obtained experimentally with a radius of ≥80mrad are very promising, see Figure 1.

The setup of the novel three-hexapole corrector is sketched in Figure 2. The corrector has a mid-plane symmetry, the length and focal-length parameters are used to eliminate the sixth-order three-lobe aberration D₆ of the corrector by means of an intentionally chosen combination aberration of the aberration ray of the six-fold astigmatism A₅ with the central hexapole field (see Figure 2).

This term acts against various internal combination aberrations of the three-fold astigmatism A₂ and the fourth-order three-lobe aberration D₃ with all three hexapole fields – also contributing to the intrinsic D₆. Together with the objective lens itself, all spherical aberrations (up to including C₇) vanish, while the total chromatic aberration is not larger compared to that of the advanced hexapole correctors [11].
OL gap $\approx$ 5mm | no corrector | conventional ($C_S \approx 0$) | advanced ($A_5 \approx 0$) | new corrector ($D_6 \approx 0$) 
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$\pi/4$-limit | 5...7mrad | 27...30mrad | 35...40mrad | $\geq 70$ mrad 
first residual | $C_S \approx 1$ mm | $A_5 = 6...3$ mm | $D_6 = 9...2$ mm | $G_7 \approx 0.5$ mm, $D_8 \approx 8$ mm 

Table 1. Hexapole corrector generations. The typical size of residual intrinsic aberrations and the resulting $\pi/4$-limits for 30...300kV are indicated, assuming a medium-size objective lens gap.

Figure 1. A comparison of experiment al in-focus conchigrams at 200kV: a) advanced hexapole corrector with $D_6 \approx 3$ mm b) calibration with gold c) new corrector with $D_6 \approx 0$.

Figure 2. The setup of the new corrector with three hexapoles. The Gaussian fundamental rays (black) are indicated together with the aberration ray $u_{A5}$ of the six-fold astigmatism of fifth order (red).

References:

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