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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 A_5 limited the maximum aperture size for probe-forming systems. Meanwhile, three different approaches have been realized to eliminate A_5 [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 D_6 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 D_6 in the order of several π/4 are reasonably counterbalanced by lower-order aberrations of the same multiplicity, D_6 hardly limits the obtainable resolution [8, 10]. However, if the intrinsic sixth-order limitation due to D_6 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 D_6 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 D_6 of the corrector by means of an intentionally chosen combination aberration of the aberration ray of the six-fold astigmatism A_5 with the central hexapole field (see Figure 2).

This term acts against various internal combination aberrations of the three-fold astigmatism A_2 and the fourth-order three-lobe aberration D_4 with all three hexapole fields – also contributing to the intrinsic D_6. Together with the objective lens itself, all spherical aberrations (up to including C_7) vanish, while the total chromatic aberration is not larger compared to that of the advanced hexapole correctors [11].

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OL gap ≈ 5mm	no corrector	conventional ($C_S \approx 0$)	advanced ($A_5 \approx 0$)	new corrector ($D_6 \approx 0$)
π/4-limit	5...7mrad	27...30mrad	35...40mrad	≥70mrad
first residual	C_S ≈1mm	A_5 = 6...3mm	D_6 = 9...2mm	$G_7 \approx$ 0.5mm, $D_8 \approx$ 8mm

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

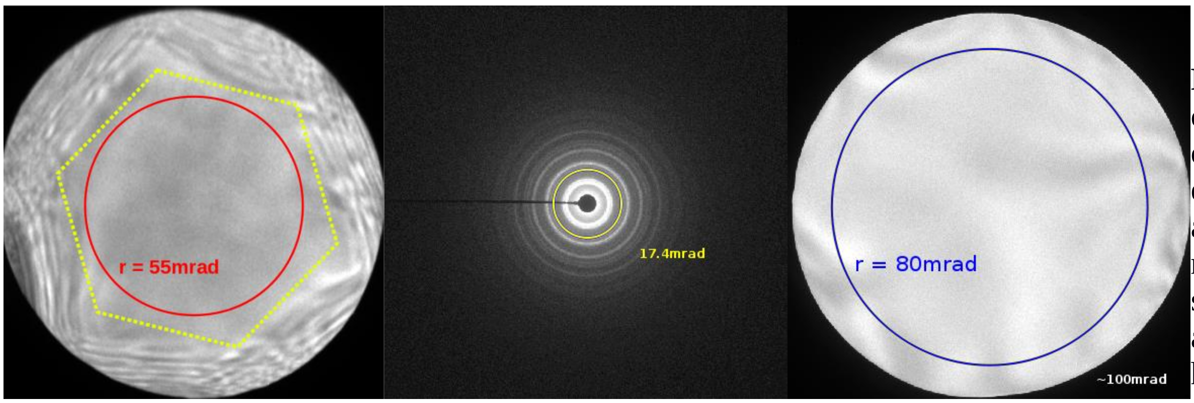

Figure 1. A comparison of experimental in-focus ronchigrams at 200kV: a) advanced hexapole corrector with $D_6 \approx$ 3mm b) calibration with gold c) new corrector with $D_6 \approx 0$.

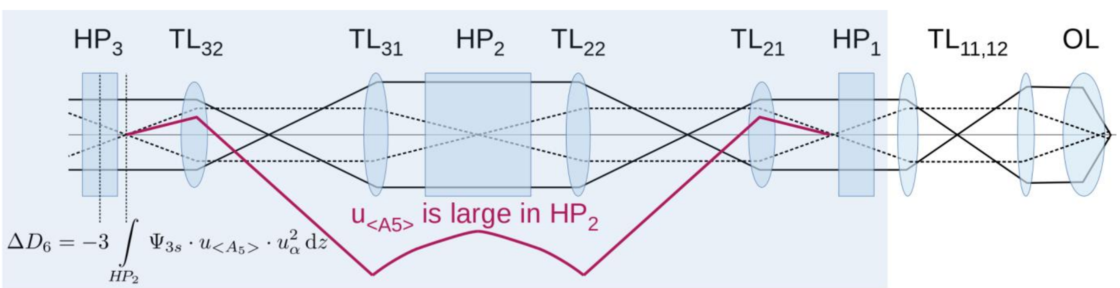

Figure 2. The setup of the new corrector with three hexapoles. The Gaussian fundamental rays (black) are indicated together with the aberration ray $u_{<A5>}$ of the six-fold astigmatism of fifth order (red)

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