Optimized Quadrupole-Octupole C_3/C_5 Aberration Corrector for STEM

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The ideal location for an aberration corrector in an electron-optical column is at the place where the aberration is introduced. In practice, this of course typically cannot be achieved. The resultant separation between where an aberration is introduced and where it is removed produces combination aberrations for all aberrations of higher than first order. In the case of third-order aberration ($C_3 \equiv C_s$) correctors, the physical separation between the objective lens which introduces the aberration and its corrector results in fifth-order spherical aberration (C_5).

In the Nion second-generation aberration corrector for scanning transmission electron microscopes (STEMs), we minimized this effect by placing the corrector as close as possible to the objective lens, and by keeping the length of the corrector to a minimum. This made the resolution-limiting fifth-order aberrations small. The advantage of the approach was that it minimized both the complexity of the instrument, and the chromatic aberration (C_c) of the probe-forming column due to the corrector. The validity of the approach has been confirmed by the fact that this corrector has produced the smallest electron probe ever achieved at both 100 kV and at higher voltages [1, 2].

To produce even smaller probes, C_5 must be corrected in addition to C_3. This is best done by projecting all the third-order elements (both aberration-causing and aberration-correcting), onto the same optical plane [3]. We have designed and built a new C_3/C_5 (third-generation) quadrupole-octupole corrector that operates on this principle. The corrector has 19 elements: 16 quadrupoles and 3 combined quadrupole-octupoles. The quadrupoles are arranged in groups of four (=quadruplets), with one quadruplet each at the entrance and the exit of the corrector, and a quadruplet between each neighboring pair of quadrupole-octupoles. There is also a further quadrupole triplet between the corrector and the objective lens. Together, the quadrupoles provide enough degrees of freedom to project the octupoles of the corrector onto each other, and then project them near the objective lens coma-free plane, onto a plane such that the fifth-order aberrations of the entire probe-forming system vanish. Seventh-order aberrations then determine the geometric aberration performance of the column, and typically limit the resolution less than the first-order chromatic aberration does.

In C_3/C_5 correctors, there are 33 aberrations that need to be monitored and properly adjusted: $C_{1,0}$, $C_{1,2a}$, $C_{1,2b}$, $C_{2,1a}$ etc. through $C_{6,7b}$ (see [4] for our aberration notation system). They mostly depend non-linearly on the transverse and axial alignment of the beam trajectories. Manual tuning of the corrector, which could still be performed by skilled operators for C_3-only correctors, is no longer possible. Accordingly, we have developed software that automatically measures and corrects the transverse and axial alignments within the corrector and thereby automates the adjustment of higher-order aberrations. Due to the stability of the corrector, it does not need to be readjusted during operation. The procedure is highly automated, and we expect the practical adjustment of our C_3/C_5 corrector to be easier than the adjustment of a typical non-aberration-corrected electron microscope.

The corrector can be set up for different optical solutions. We have tested two types of solutions (Fig. 1): 1) a skew-symmetric solution, in which the beam is elliptical in octupoles one and three and round in octupole two, and the trajectories in the X-Z plane are identical to backward-running Y-Z trajectories, and 2) an asymmetric solution with a round beam in octupole one and elliptical beam in octupoles two and three [5]. The asymmetric solution has slightly higher seventh-order aberration coefficients, but much reduced C_c: 0.2 mm for the corrector, as opposed to the symmetric solution's 0.4 mm. The asymmetric solution also decreases the number of strong quadrupoles and minimizes axial beam widths everywhere except in the octupoles. This results in relaxed alignment tolerances and a reduced sensitivity to power supply instabilities.

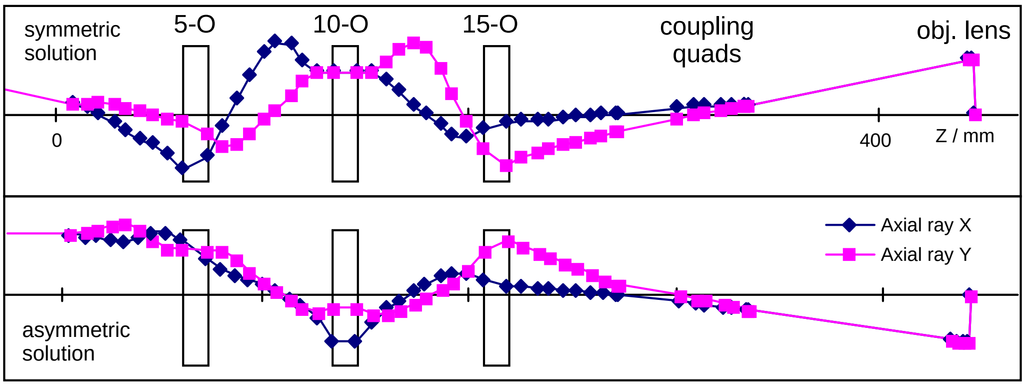

Fig. 1. Axial trajectories of two types of optical solutions for the new corrector. The beginning and end of each quadrupole, quadrupole-octupole and the round objective lens are marked by the small squares (and diamonds). The three quadrupole-octupoles, schematically denoted by large rectangles, are situated in corrector layers 5, 10 and 15.

With an objective lens of f=1.5 mm and C_s=1.0 mm plus optimal compensation of seventh-order aberrations by lower order ones, the geometric resolution of the new probe-forming system is limited by eight-fold astigmatism ($C_{7,8}$) of 12 mm. The largest usable illumination angle is then:

$$\theta_{max} = (2\lambda / C_{7,8})^{1/8} \tag{1}$$

This gives a maximum theoretical illumination half-angle of 67 mrad (nearly 4 degrees) at 200 kV. However, in our system with C_c=1.2 mm and energy spread ΔE=0.3 eV, this is reduced by chromatic effects to about 40 mrad and hence a resolution of 0.4 Å. A 40 mrad illumination half-angle will increase the beam current available in given-size probes, and will also improve the depth resolution of through-focal 3-D reconstruction. On the other hand, illumination angles of this order will result in a significant portion of the atomic scattering falling within the bright-field cone, a problem likely to become especially severe for light atoms. The resultant decreased efficiency of high-angle dark field [HADF] imaging may mean that, just like with high-quality optical cameras, the optimum size of the beam-defining aperture in the new system will typically be the one best suited to the task at hand, rather than the largest possible. When this becomes the norm rather than the exception, STEM electron optics will have truly progressed beyond the traditional "aberration-limited" era.

References:

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[4] O.L. Krivanek et al., Ultramicroscopy **78** (1999), 1
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