Design and Testing of a Quadrupole/Octupole C_3/C_5 Aberration Corrector

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The ideal location for an aberration corrector in an electron-optical column is exactly at the place where the aberration to be corrected is introduced. In practice, this of course 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. A case of particular importance to electron optics is third order aberration (C_s) correctors. For which a physical separation between the objective lens, which introduces the aberration and the corrector, which removes it, results in fifth order spherical aberration ($C_{5,0}$).

In the Nion second-generation corrector, 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, it becomes necessary to project all the third order elements (both aberration-causing and aberration-correcting), onto the same optical plane [3]. We have therefore designed a quadrupole-octupole corrector with a total of 19 elements: 16 quadrupoles and 3 combined quadrupole-octupoles. The quadrupoles are arranged in 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 to project them collectively near the objective lens coma-free plane, into a plane such that the fifth order aberrations of the entire probe-forming system vanish.

In a practical implementation of a higher order aberration corrector it is essential that a highly automated alignment system is developed. A skilled operator can separate and correctly adjust aberrations of different angular dependence. In other words, $C_{1,0}$, $C_{1,2}$, $C_{2,1}$, $C_{2,3}$ and $C_{3,4}$ (see [4] for an explanation of our notation system) can be manually adjusted as long as there are reasonably pure controls available. In a C_5-limited corrector a straightforward set of linear controls for adjusting $C_{1,0}$, $C_{1,2}$, $C_{2,1}$, $C_{2,3}$, $C_{3,0}$, $C_{3,2}$ and $C_{3,4}$ can be generated, and $C_{4,1}$, $C_{4,3}$ and $C_{4,5}$ can be kept at a non-performance-limiting level through proper zeroth order alignment.

In the C_7-limited corrector, however, there are 15 additional degrees of freedom, $C_{5,0}$ through $C_{6,7}$, which need to be minimized. Just like $C_{4,1}$ through $C_{4,5}$, they are non-linearly dependent on the transverse and axial alignment of the beam trajectories. We are therefore developing software that simultaneously determines the residual aberrations and the system responses, and automatically adjusts the trajectories. This system will automate the adjustment of higher order aberrations, in the same way that the lower order aberrations $C_{1,0}$ through $C_{3,4}$ are now automatically adjusted. Despite, or perhaps thanks to, the complexity of the alignment for optimum performance, we expect that the operation will, in fact, be simpler than the operation of non-aberration-corrected microscopes.

Using an objective lens with f=1.5 mm, C_s=1.0 mm in the new probe-forming system, while optimally compensating seventh order aberrations using lower order aberrations, the resolution-

limiting aberration becomes $C_{7,8}$=10 mm. Its value determines the largest illumination angle that can be utilized:

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

(1)

This gives the maximum theoretical half-angle for our new system to be 68 mrad (nearly 4 degrees) at 200 kV. Such a large illuminating angle will greatly increase the available beam current. It will also result in a greatly limited depth of focus, making it possible to use through-focal image variation for 3-D reconstruction.

The theoretical diffraction-limited probe size corresponding to 68 mrad illumination half-angle is $d = 0.61\lambda/\theta = 0.23$ Å. We do not, however, expect to reach such a value in practice, for several reasons: chromatic aberration, lack of precision of practical autotuning and instrumental instabilities. The corrector adds only 0.2 mm to the total C_c of the probe-forming optics and the energy spread of the CFEG is only about 0.3 eV, but even so chromatic effects will prevent the probe size from being smaller than 0.4 Å at 200 kV.

With the correcting elements projected onto the proper plane of the objective lens, it is also possible to scan the beam before the corrector, or to use the same type of corrector for CTEM applications. In order to characterize the performance under these conditions, we need to consider the off-axial aberrations of our electron-optical column. This is best done by extending our axial aberration notation system by adding superindicies to the axial aberration coefficients, to indicate the change in axial aberrations across the sample (or image) plane. Using polar spatial coordinates r, α defined in the plane of the sample and beam angles θ, φ, the extended-definition aberration function is then given by:

$$\chi(r,\alpha,\theta,\varphi) = \sum_C \frac{1}{m+1} C_{m,na}^{u,va} \cos_1(v\alpha) r^u \cdot \theta^{m+1} \cos_2(n\varphi)$$

(2)

If the superscript suffix is b instead of a, $\cos_1$ is replaced by sin. Likewise, if the subscript suffix is b, $\cos_2$ is replaced by sin. For rotationally invariant aberrations, the a or b suffix is absent, and there is no cos. In contrast to the axial aberration subscripts, the field superscripts consist of two numbers both either even or odd. For our new corrector, we find the aberration limiting the field of view to be $C_{2,3b}^{1,1b}$=1.27 [unitless], which limits the width of the field of view to 50nm at the 0.5Å resolution level. For larger fields of view, $C_{1,2a}^{2,2a}$=-3.3×10^5 m^{-1} limits the field of view to 180nm at the 1Å level.

In summary, we have designed a new aberration corrector that combines the desirable properties of quadrupole-octupole correctors, such as low power consumption and greater immunity to misalignment effects, with the ability to correct aberrations of fifth order. Detailed testing of the new system is presently in progress, and results will be reported at the meeting.

References

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