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Zernike Phase Contrast Electron Microscopy with a Spherically Corrected Foil Lens

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In a paper, published in 1980 on the occasion of the 80th birthday of his old colleague and friend Ernst Brueche, Otto Scherzer proposed a specific lens system that uses a thin foil in the optical path on which charges are inducted for correcting the spherical aberration [1]. He had in fact already proposed a similar system as one of the possible ways for spherical correction in his 1949 paper [2], a possibility that was later also persued by other authors [3-5]. His new idea was to provide a hole in the foil for the primary beam to avoid contamination or damage by the strong central beam. In his design proposal, the foil is inserted directly below the rather thin and relatively wide open lower pole piece of the objective lens. The electric field for inducing the charges on the foil is essentially restricted to the side of the foil away from the lens. He assumes the foil to be so thin that the phase shift within the foil can be neglected. For an accelerating voltage of 60 kV, a relatively large focal length of 10 mm, and a maximum aperture angle of $\theta_m = 0.1$ rad, he expects that a resolution far below 1 Angstrom can be reached. The nominal resolution limit, $d = 0.6\ \theta_m/\lambda$ would be 30 pm, and the transmitted area of the foil would be 2 mm in diameter under this condition. The diameter of the central hole is not assumed to be very small as he intends to use (dynamic) hollow cone illumination for optimizing the resolution and minimizing the depth of focus. His aim is to visualize single light atoms such as carbon or nitrogen in not extremely thin (up to 100 Angstroms) specimens. He made the design proposal at a time when the progress of spherical and chromatic correction with non-axially symmetric elements that he was pursuing in his lab was stagnating at a resolution of about 2.5 nm. It seems that nobody has tried to realize the proposed system. After spherical correction with a hexapole corrector had become available [6], Scherzer's proposal was largely forgotten.

From the present point of view, considering the fact that in-focus Zernike phase contrast has recently successfully been implemented using a thin carbon film of appropriate thickness [7,8], one might again consider Scherzer's proposal, but modified so as to use the inner potential of the carbon film to provide phase contrast that extends down to very low spatial frequencies. At the accelerating voltage of 60 kV, the thickness of a carbon film for obtaining a quarter wave length phase shift would be about 18 nm. It is questionable that a carbon film much thinner than that, or even an 18 nm thick film, would be stable enough to span an area that is 2 mm in diameter. On the other hand it would be a great advantage to combine in-focus Zernike phase contrast with Scherzer's idea of spherical correction.

The stability of the film can be improved by increasing the accelerating voltage. Using 300 kV instead of 60 kV reduces the scattering angles by a factor 2.5; at the same time the thickness of the film for a $\pi/2$ phase shift is increased from about 18 to 31 nm. Combining this with a reduction of the focal length to 5 mm, the diameter of the film will be reduced to 400 µm for the extreme case of 30 pm nominal resolution. According to Scherzer, the maximum field strength within the transmitted area of the film mainly depends on the focal length, f, and the spherical aberration onstant, C_s, i.e. it is for an intended resolution not increased by increasing the accelerating voltage

Apart from the stability problem of the thin film, there is the problem of charging of the film due to contamination. This problem has largely been solved by heating the film to about 200 °C [8]. In

Scherzer's design the element is so close to the lens that it will not be possible to insert an aperture in front of the correcting element that protects the specimen from thermal radiation. This is one main reason that we propose to use a transfer lens system and to insert the correcting element in an image of the diffraction plane. The objective lens could then have a short focal length of, say, 2.5 mm. The first transfer lens increases the diffraction pattern by a factor of two so that the effective focal length in the diffraction plane will be 5 mm. An additional advantage of placing the system farther away from the objective lens is that charges can be induced on both the front and the back side of the film. The field stengths within the correcting system will thus be the same as in the system with twice the focal length. A point that has to be considered is that the so-called combination error, that contributes to the 5th order spherical aberration, might become large [9]: Due to the spherical aberration of the objective lens, an off-axial ray arives at a somewhat larger distance from the axis in the second transfer lens and is therefore, due to the spherical aberration of this lens, more strongly deflected. An estimation shows that this error can be kept within reasonable limits.

Since such a lens system will not be chromatically corrected, the microscope needs to be equipped with a monochromated electron source. Scherzer himself mentions that for a resolution limit below about 0.8 Angstroms the 5th order spherical aberration needs to be corrected, which can be achieved by slightly changing the form of the positive electrodes.

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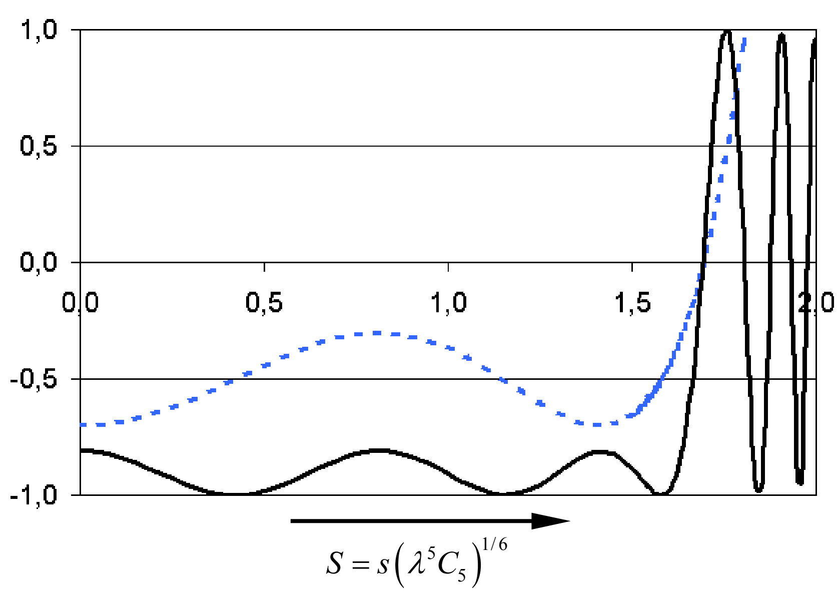

Figure: Optimum phase shift γ/π of the scattered waves against the primary wave (▬ ▬ ▬), and (ideal) phase contrast transfer function (CTF) of a TEM with a spherically corrected Zernike phase plate; S is the normalized spatial frequency, s the spatial frequency, λ the wave length, and C_5 the constant of the 5th order spherical aberration. For 300 kV accelerating voltage and C_5 = 30 mm, the normalized frequency S = 1.0 corresponds to s = 1/(100 pm); the first zero of the CTF is at s = 1/(60 pm).

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