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Effect of a Physical Phase Plate on Contrast Transfer in an Aberration-Corrected Transmission Electron Microscope

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Motivation

- Novel TEM imaging techniques by realization of "physical" phase plates (PP) [1]
- Cs-corrector [2,3] allows in principle full correction of aberrations up to the fifth order, but contrast vanishes for weak-phase objects without aberrations
- Combining Cs-correction and an ideal phase plate yields optimal contrast with full correction of aberrations
- We apply the weak-phase object approximation to explore ranges for defocus Z and Cs-values resulting in optimal imaging conditions, for both phase plate imaging and conventional Cs-corrected imaging

Fig. 1: Scheme of physical phase plate positioned in the back focal plane (BFP) of the objective lens; phase shifting of either diffracted of undiffracted electrons

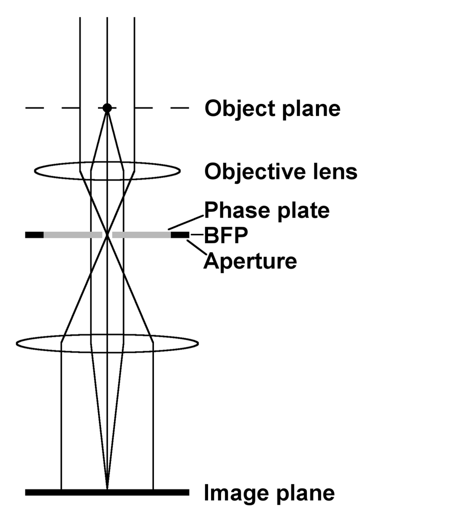

Fig. 1: PP positioned in the BFP of the objective lens

Phase Contrast Transfer

- Imaging of weak-phase objects is commonly described by the phase contrast transfer function (PCTF)
- The object wave function is Fourier transformed and multiplied by the PCTF given as

$$PCTF(u) = E(u)\cdot\sin(\chi) \qquad \chi = \pi\left(Z\lambda u^2 + \frac{1}{2}C_S\lambda^3u^4\right)$$

- Optimal phase contrast in TEM without Cs-corrector at Scherzer defocus with corresponding Scherzer resolution:

$$Z_{Sch} = -\sqrt{\tfrac{4}{3}C_S\lambda} \qquad u_{Sch} = 1.52\left(C_s\lambda^3\right)^{-1/4}$$

- Phase distortion function χ with a phase plate in the back focal plane of the microscope:

$$\chi_{PP} = \pi\left(Z\lambda u^2 + \frac{1}{2}C_S\lambda^3u^4\right) + \phi_{PP}$$

- Optimal phase contrast conditions for uncorrected phase plate imaging are given according to [4] by

$$Z_{Sch,pp} = -0.73\sqrt{C_s\lambda} \qquad u_{Sch,pp} = 1.4\left(C_s\lambda^3\right)^{-1/4}$$

Cs-Correction & Phase Plates

- Optimal parameters for imaging without a phase plate but with Cs-correction described by Lentzen et. al. [5]
- Scherzer resolution is not extended far beyond the information limit of the microscope, as well as delocalization is minimized
- Optimal defocus und Cs-value are given as

$$C_{S,opt} = \frac{64}{27}\frac{1}{\lambda^3u_{\inf}^4} \qquad Z_{opt} = -\frac{16}{9}\frac{1}{\lambda\, u_{\inf}^2}$$

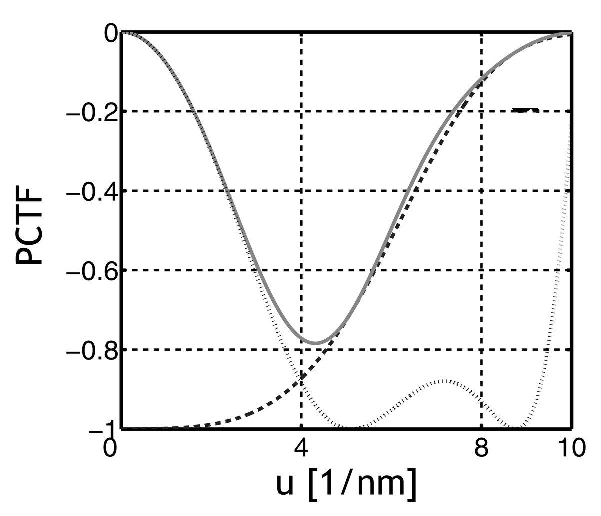

Fig. 2: PCTF (solid gray line), sine-function of wave aberration sin(χ) (dotted line) and envelope function (dashed black line) for 200 keV microscope with an information limit of 0.12 nm

- Fig. 2: Low contrast transfer at small and intermediate spatial frequencies compared to high contrast transfer at these frequencies with the use of a phase plate (Fig. 3 a)
- Optimal theoretical values for defocus and Cs-value are obviously Cs = 0 mm, Z = 0 nm and $\phi_{pp} = \pi/2$ with phase plate and Cs-correction
- Fig. 3: Contrast transfer for Cs=1 µm and different defoci; phase contrast is reduced and the PCTF starts to oscillate at larger defocus values

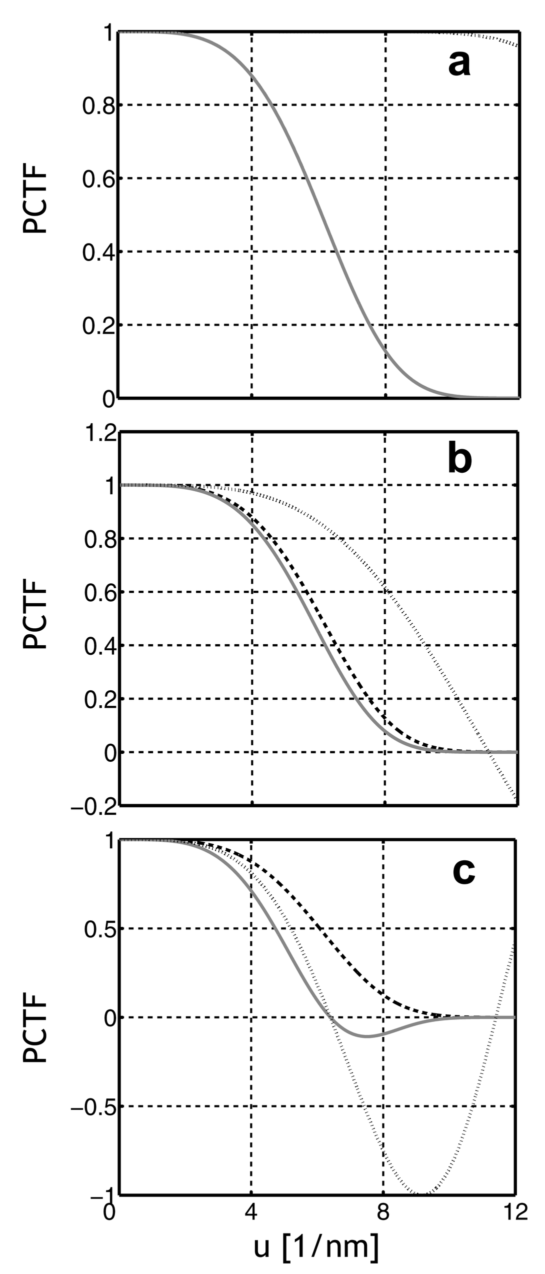

Fig. 3: PCTF as in Fig. 1, but with a phase shift $\phi_{pp} = \pi/2$ and fix Cs-value of Cs = 1 µm for different defocus:
a) Z = -0.2 nm, b) Z = -2.0 nm and c) Z = -5 nm

Quantification of Phase Contrast

- Influence of defocus and Cs-values on phase contrast (PC) quantified by integrating the PCTF

$$PC = \int_0^{u_{\inf}} E_t\,E_s\left|\sin\left(\chi_{pp}\right)\right|du$$

- Comparison with optimal phase contrast

$$PC_{id} = \int_0^{u_{\inf}} E_t\,E_s\,du$$

- Fig. 4: PC for a 200 keV phase plate microscope and a normal 200 keV microscope; black lines denote 5% (10%) reduction with respect to PC_{id}.

$$\frac{PC_{id} - PC}{PC_{id}} < 0.05\ (0.1)$$

- Consideration of Delocalization R: white lines in Fig. 4 denote delocalization corresponding to Lentzen parameters

$$R_{len} = \frac{16}{27}u_{\inf}$$

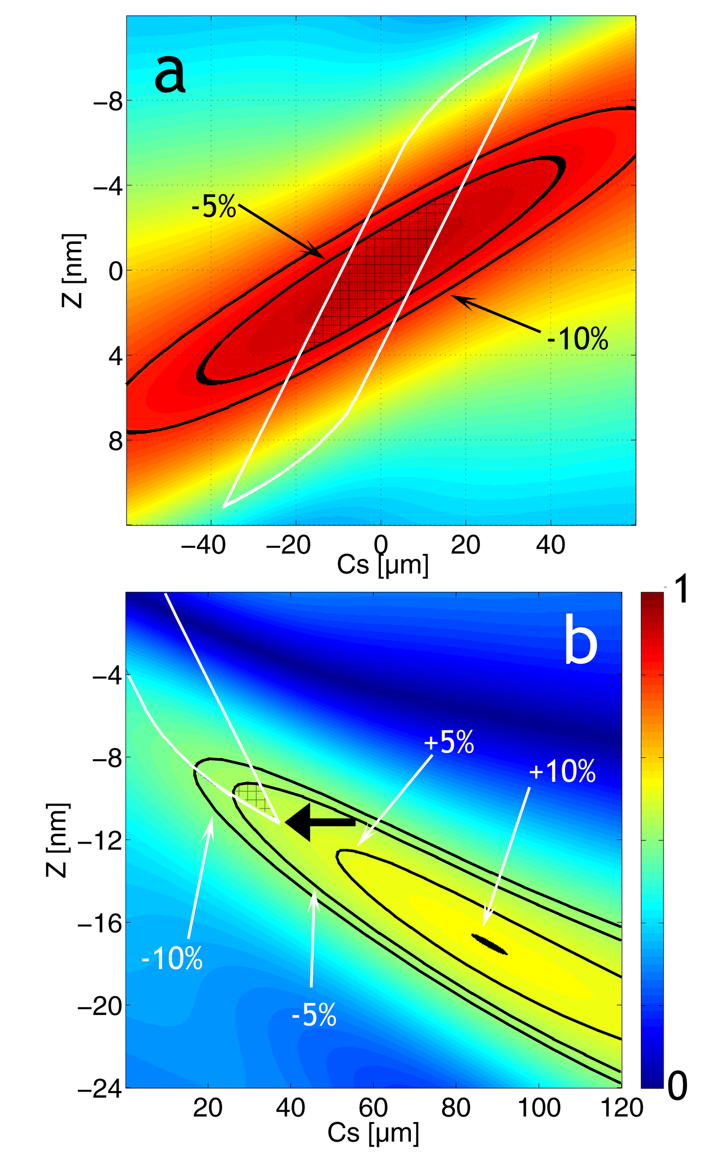

Fig. 4: Color-coded values of PC for 200keV microscopes, a) with phase plate b) without phase plate. Color represents derivation form optimal PC-value. Black arrow in b) points at Lentzen parameters for the given microscope.

- Fig. 5 shows defocus ranges for a 200 keV and a 300 keV microscope fulfilling the 5 %-criteria for the phase contrast integral versus the information limit
- Phase contrast microscopes (gray lines) show wider defocus ranges, i.e. permitting a rougher sample-surface topography at same resolution and eventually a larger sample region to be imaged.
- 300 keV microscopes show a slight advantage compared to 200keV microscopes.

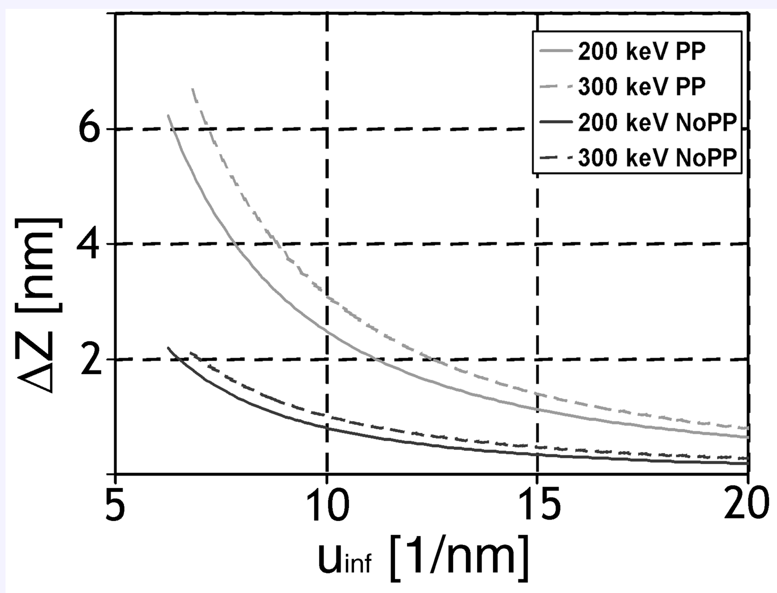

Fig. 5: Defocus ranges for 200 keV and 300 keV microscopes fulfilling 5%-criteria for the PC-Integral

Real Phase Plates

- Real Boersch phase plates show an electrode ring completely obstructing information for a certain region of low frequencies (object features larger than approx. 5.5 nm for a typical 200keV microscope)
- Calculations for Fig.4 and Fig. 5 have been done with Boersch geometry considered and it was found that the loss of information sums up to approx. 8% for a 200keV microscope (3% for a 300keV with 0.05 nm information limit)

Summary

- Almost perfect coincidence of the phase contrast transfer function with the envelope function for partial temporal coherence even for future microscopes with next-generation correctors possible
- In-focus phase contrast with a Boersch phase plate will provide strong and localized object contrast over the entire resolution range in one single image
- Effective interpretable field of view increases for in-focus phase contrast imaging, due to reduced delocalization

References

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Acknowledgements

The project is funded by the German Research Foundation (Deutsche Forschungsgemeinschaft) under Ge 841/16 and Sch 424/11.