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Is there a Road Map of Aberration Correction towards Ultra-High Resolution in TEM and STEM?

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Until the mid of the nineties it was assumed aberration correction is too complicated to be ever used for routine work. However, with the emergence of aberration correctors for high-resolution electron microscopes a new generation of microscopes has been made available. This stimulating development of aberration correctors was first successful with a dedicated Low Voltage Scanning Electron Microscope for which the chromatic and the spherical aberration have been cancelled [1]. About two years later a spherical aberration corrected 200 kV TEM could be finished [2] and a Cs-corrected STEM was completed [3] again one year later. The first installations of spherical aberration corrected EMs have shown new results and have proven the possibility to improve the resolution of an EM by means of an aberration corrector [4]. These developments are, however, not finished and the current state and possible future directions will be discussed.

In addition to these exciting developments several groups demonstrated the reduction of the energy spread of the electron beam by means of a monochromator. This has proven to further improve the information limit of a TEM equipped with a Schottky-emitter as has been shown by [5] and recently by ZEISS [6]. Additionally, aberration corrected energy filters with increased dispersion became available for spectroscopy and spectroscopic imaging during the last years.

Today, after the installation of the first generation of Cs-corrected TEMs and STEMs the question arises: What are the next developments and how will the future microscope look like? The "Road Map" splits in two trends for the future: On one side the improvement of the ultimate resolving power is always the driving parameter for future developments and on the other side the extended applicability with, for example, larger pole-pieces gaps will become at least as equally important.

The availability of Cs-correctors for TEM and STEM already had a strong impact on the imaging science. For TEM bright-field imaging, for example, the imaging of light elements and, furthermore, the measurement of the occupancy of oxygen in ceramics [7] with a precision of about 10% has been demonstrated. Delocalisation effects at interfaces are no longer present and TEM dark-field imaging with atomic resolution is now possible. The improved resolving power of a Cs-corrected STEM helps to image single atoms with improved contrast [8], since the beam current at a given probe size is increased by about one order of magnitude, owing to the increased illumination cone.

After having demonstrated the possibilities and advantages of spherical aberration correction in electron microscopes it was immediately clear that the achievable resolution is now set by the instrument itself. Unfortunately, the information limit of the currently existing modern instruments set by the incoherent perturbations, for example internal and external time varying fields and chromatic image blur, has not improved as dramatically as their electron-optical properties have. It turns out, that the improvement of the information limit is now the most crucial step to exploit the full benefits of aberration correction.

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Thus, the task list for future developments must be:

1. **Improve the information limit** of the EM in order to achieve the theoretically attainable resolution on a daily basis by improved stability (electrically and mechanically) and decrease the sensitivity of the EM against disturbances from the environment.
2. Further **improve the electron optics** in terms of understanding, and cancellation or minimization of higher-order axial aberrations in 4th through 7th order.
3. Owing to the increased size of CCD-cameras an increased number of equally well resolved image points will be desirable in the future. This imposes new demands on the electron-optical development and the **correction of off-axial aberrations must be considered**.
4. The dominant resolution limiting aberration however, the chromatic aberration Cc, has not yet been compensated for a high resolution TEM. Hence, an aberration corrector which combines the three above mentioned corrector systems, the correction of spherical aberration Cs, the off-axial aberrations and the **chromatic aberration Cc**, is the goal of the foreseeable future. Such a highly sophisticated corrector would solve the needs for ultra high resolution TEM aiming for about 50 pm resolution and it would also be the system of choice for in-situ or Lorentz Microscopy where large pole piece gaps are a prerequisite.
5. The final step of development would be to further **improve the easiness** of operation of the even more complex EMs in the future and make all advantages of aberration-corrected imaging available for even for the average user while giving the expert full control over the optical properties of the system

According to this development scheme the first step is done and the second is just in progress while the other steps will be carried out within the coming 5 – 10 years from now on. Hence, the achievements of Cs-corrected EM have led to the initiation of various national projects in the US (e.g. TEAM [9]), in Japan, and in Europe in order to carry on these developments and to provide the latest techniques to the research institutes, which will benefit from theses ultra-high resolution instruments.

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