

## Performance of the SALVE-microscope: Atomic-resolution TEM Imaging at 20kV

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The SALVE project had been initiated to develop a dedicated low-voltage TEM that is corrected for both, spherical and chromatic aberration, in order to allow atomic resolution TEM observations on beam sensitive materials [1,2].

The centerpiece of the SALVE III microscope is CEOS' new Cc-Cs-corrector that is based on the so-called Rose-Kuhn-Design [3,4]. The corrector is incorporated into a cubed FEI Titan Themis TEM and has been aligned for five accelerating voltages in the range from 20 to 80kV.

During corrector design special care had to be taken to avoid the resolution limiting effects of thermal magnetic field noise (Johnson-Nyquist noise) that effectively limits the information transfer in Cc-corrected electron microscopes [5]. As seen in Table 1, these measures have been successful in that for all desired high-tensions the resulting final resolutions exceed the desired 50mrad aperture. Figure 1(a) exemplarily demonstrates the achieved information limit at an accelerating voltage of 20kV. For the two perpendicular directions the Young's fringes on a purely amorphous 2nm tungsten sample significantly exceed the 50mrad radius. In order to "use" the transferred information adequately, the phase plate, i.e. the aberration function, has to be well-controlled beyond the 50mrad-angle. This requires access up to including 5th order axial aberrations, and -for a considerable field of view- control over off-axial aberrations. The aberration measurement in Figure 1(b) demonstrates that all unround axial aberrations as well as the off-axial aberrations can be tuned sufficiently small. At the same time, the round aberrations can be adjusted for a suitable phase contrast transfer function (indicated in green color). Consequently, as visible in Figure 1(c) atomic resolution imaging at 20kV becomes reality.

Chromatic aberration causes inelastically scattered electrons, i.e. electrons of lower energy, to be focused much stronger. This is not true in the Cc-corrected instrument. Figure 1(d) compares the energy-dependent defocus effect at 20kV of a Cc-uncorrected TEM (red line, Cc=1.45mm) and the SALVE microscope (measurements: black dots, 3rd order fit: dashed line). The magnified area indicates that EFTEM with significant energy windows is possible even at 20kV enabling new modes of operation such as high-resolution EFTEM at very low voltages. [6]

### References:

[1] U. Kaiser *et al.*, Ultramicroscopy 111, Issue 8 (2011), 1239-1246.

[2] <http://www.salve-project.de/>

[3] H. Rose, Proc. 10th Eur. Congr. El. Micr. (Granada, Spain) (1992), 47.

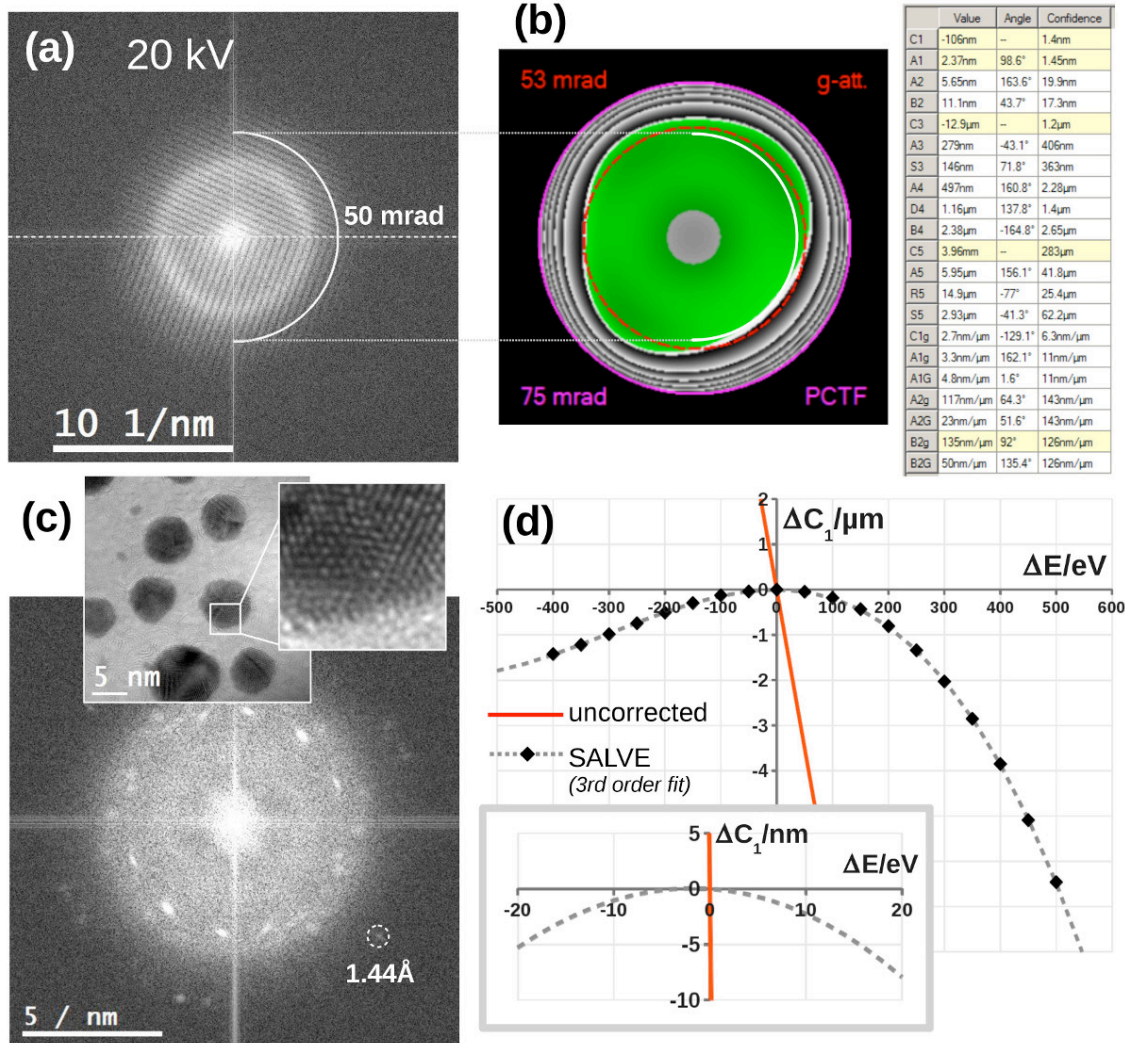
[4] H. Rose, Patent Application DE 42 04 512 A 1 (1992).

[5] S. Uhlemann *et al.*, Physical Review Letters 111(4) (2013), 046101.

[6] The authors acknowledge funding from the German Research Foundation (DFG) and the Ministry of Science, Research and the Arts (MWK) of the federal state Baden-Württemberg, Germany.

high voltage	wave length	50 mrad resolution	SALVE results
20 kV	8.589 pm	171.8 pm	139 pm
30 kV	6.979 pm	139.6 pm	115 pm
40 kV	6.016 pm	120.3 pm	90 pm
60 kV	4.866 pm	97.3 pm	83 pm
80 kV	4.176 pm	83.5 pm	76 pm

**Table 1.** Resulting information limit of the SALVE-microscope for different accelerating voltages. The resolution as determined from Young's fringes visibility on an amorphous tungsten sample significantly exceeds the 50 mrad resolution for all high-tensions.



**Figure 1.** SALVE results at 20kV: (a) The Young's Fringes resolution test (in two directions) on an amorphous tungsten sample indicates an information limit beyond the 50mrad aperture. (b) At the same time, the wave aberration can be tuned up to in 5th order for uniform phase contrast beyond 50mrad (PCTF passband in green color, corresponding aberration coefficients tabulated). (c) Atomic resolution image of gold clusters at 20kV. The 1.44 Angstrom reflections clearly show up in the corresponding FFT. (d) Defocus vs. energy offset at 20kV: Unlike the Cc-uncorrected TEM (red line) the SALVE corrector allows imaging without significant focus changes (dashed line). Within a 20eV window the defocus changes by only 2nm due to the remaining higher order chromatic aberrations.