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The Aberration Corrected SEM

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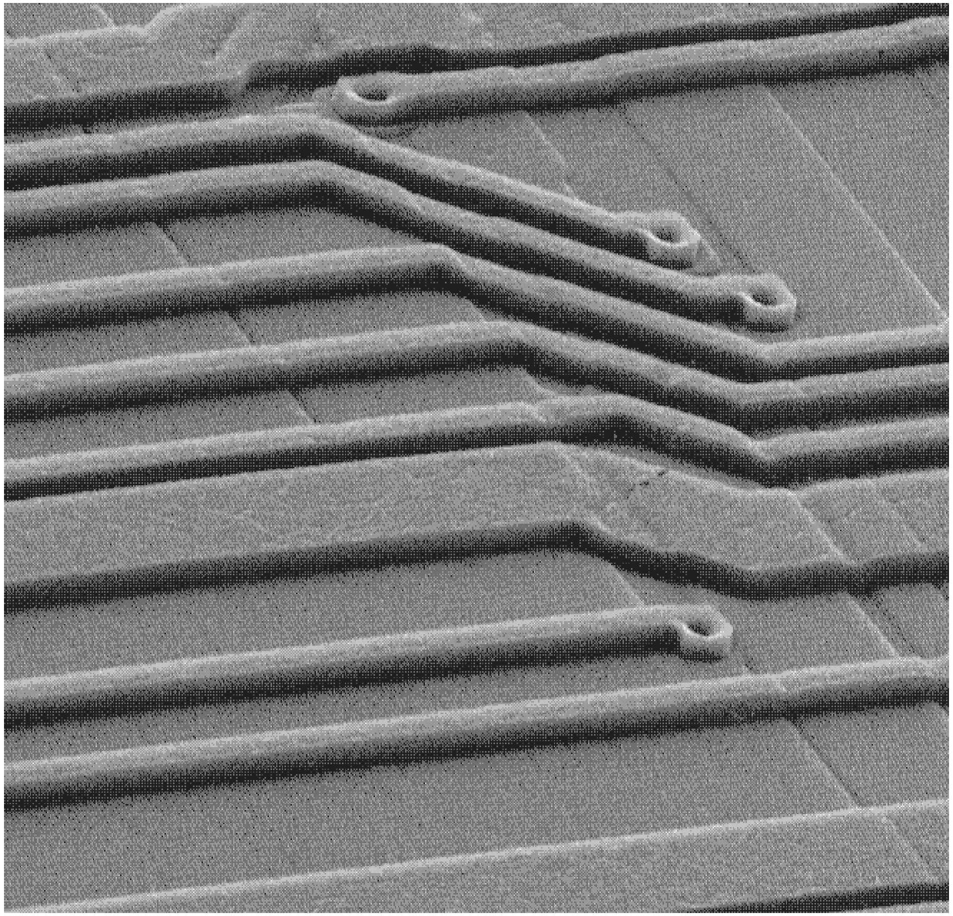
CD Metrology in the SEM

- The CD-SEM is a specialized SEM for device metrology. It typically is operated at energies between 100eV and 1keV
- Although current tools can produce nanometer resolution with enough current for high speed image collection if the CD-SEM is to be extensible to the end of the Road Map then basic limitations in the performance of the tool have to be overcome
- The most important of these are the aberrations of the electron-optical lenses



Aberrations in the CD-SEM

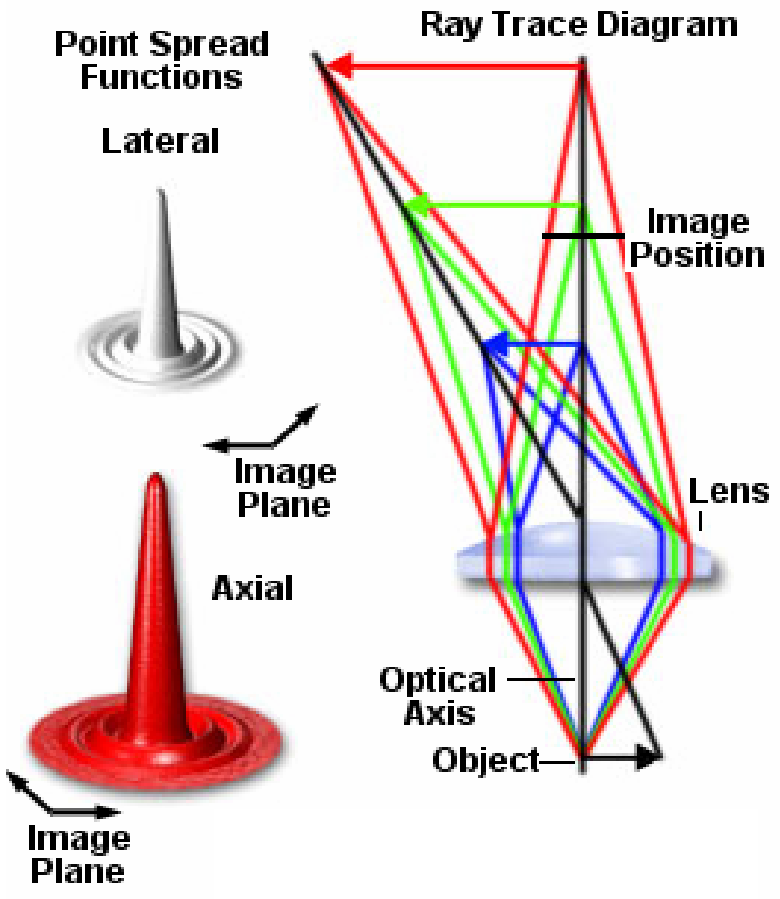
- **The three key aberrations for the CD-SEM in order of significance are;**
- **Chromatic aberration**
- **Diffraction**
- **Spherical aberration**
- **As shown by Scherzer (1936) each is inevitable and optimizing the balance between them leads to undesirable restrictions on performance**
- **Aberration coefficients scale with focal length and lens size so high performance lenses are restrictive**

What is Chromatic Aberration?

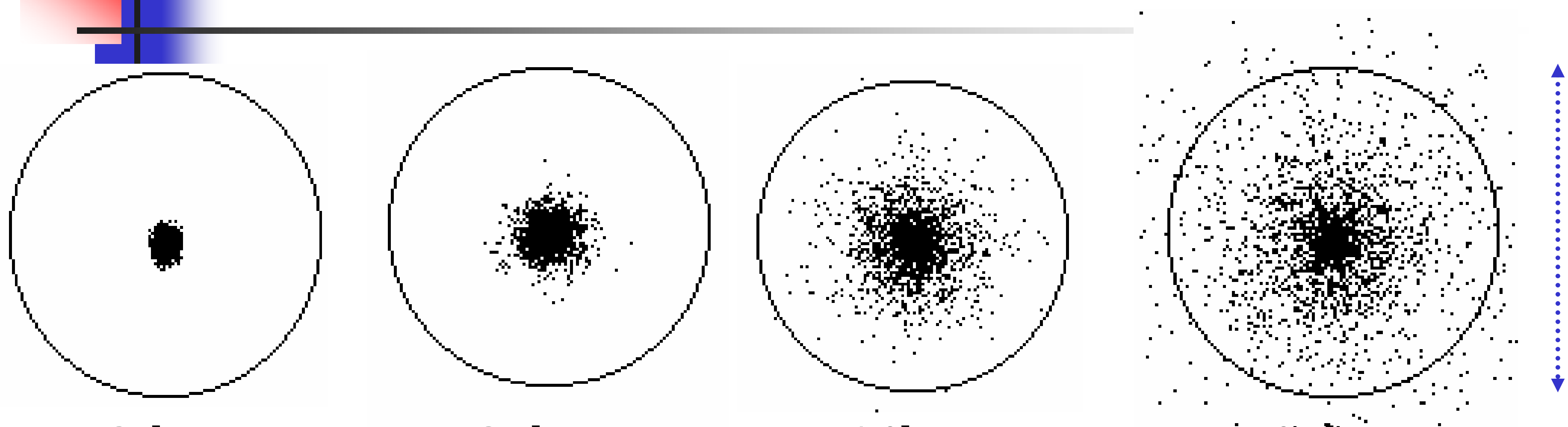
- **Chromatic aberration is the effect in which electrons of different energy are focused to different planes.**

$$Error\ \Delta z = C_c \alpha . \frac{\Delta E}{E}$$

- **Every electron source has a natural energy spread and the source of choice - the Schottky emitter - has a spread of ~ 0.7eV which is a high fraction of the beam energy when below 1keV**



Chromatic aberration and the probe



Kenway-Cliff numerical ray-tracing simulations of electron arrivals with a lens Cs=3mm,Cc=3mm, α =7 m.rads

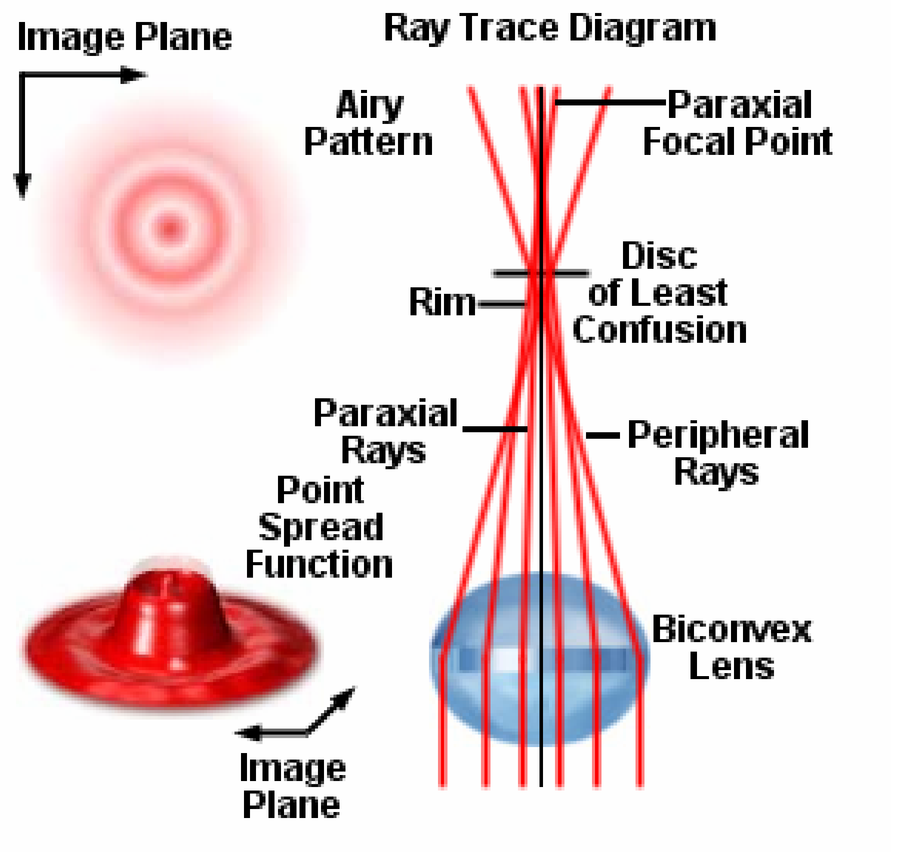
Chromatic aberration puts a diffuse ring of scattered electrons around the probe, degrading image contrast and broadening the probe size

Spherical Aberration

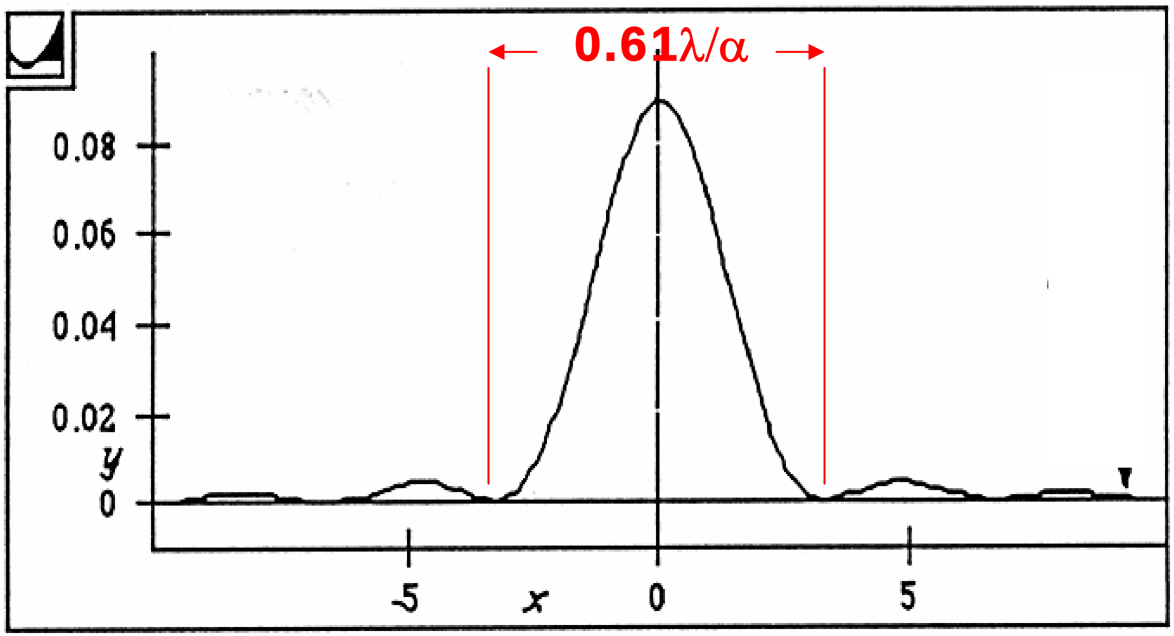
- Spherical aberration is the difference in focus between paraxial and peripheral rays

$$Error\ \Delta z = \frac{1}{2} C_s \alpha^3$$

- All electron-optical lenses have positive-definite spherical and chromatic aberration (Scherzer) so these contributions always add



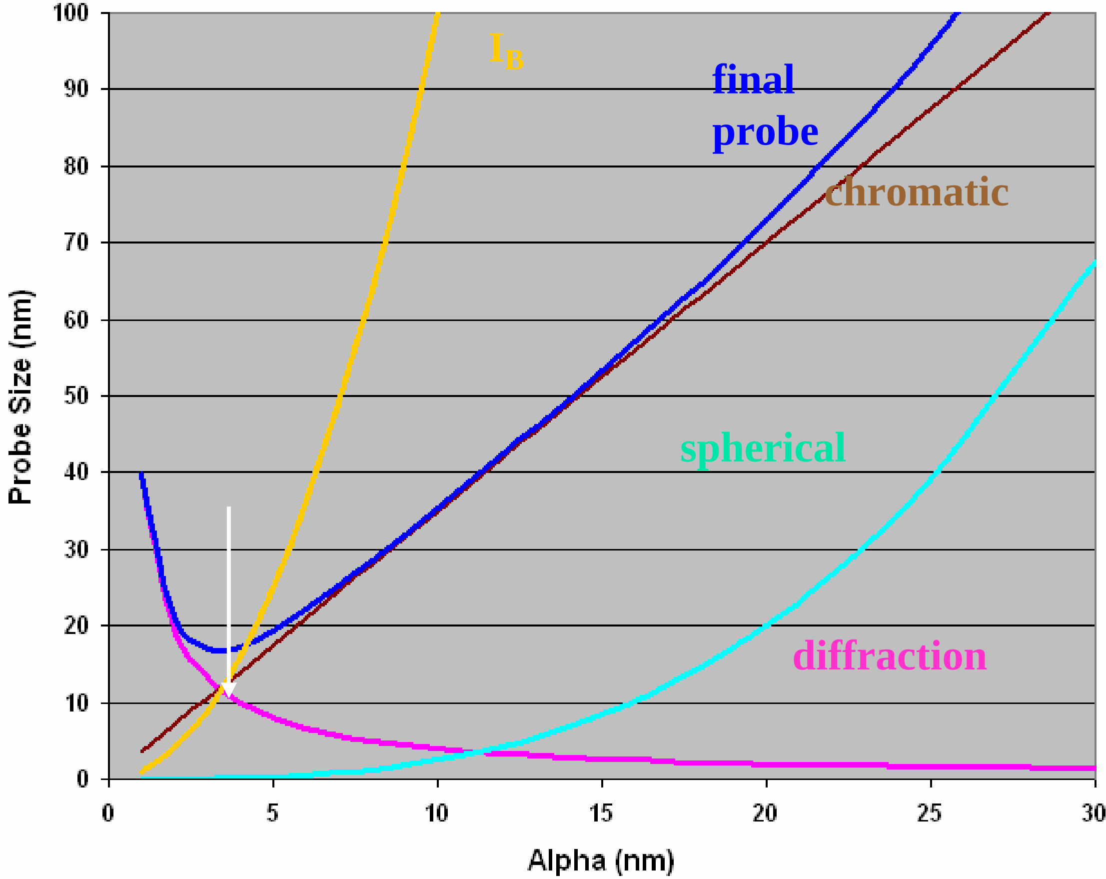
Diffraction



- Electrons are waves so when converged by a lens they form a Diffraction (Airey) Disc at the focal point with a width λ/α
- For low energy electrons λ is LARGE (0.01 to 0.05nm)

The effect of aberrations at low voltage

- Each contribution varies with α the convergence angle
- Chromatic aberration and diffraction are the largest
- Optimizing α to give the smallest probe size results, for typical optics, in a NA of only a few millirads and in a diffraction limited probe of size ~18nm
- The low NA severely limits the current into the probe and so degrades the image SNR and hence the throughput

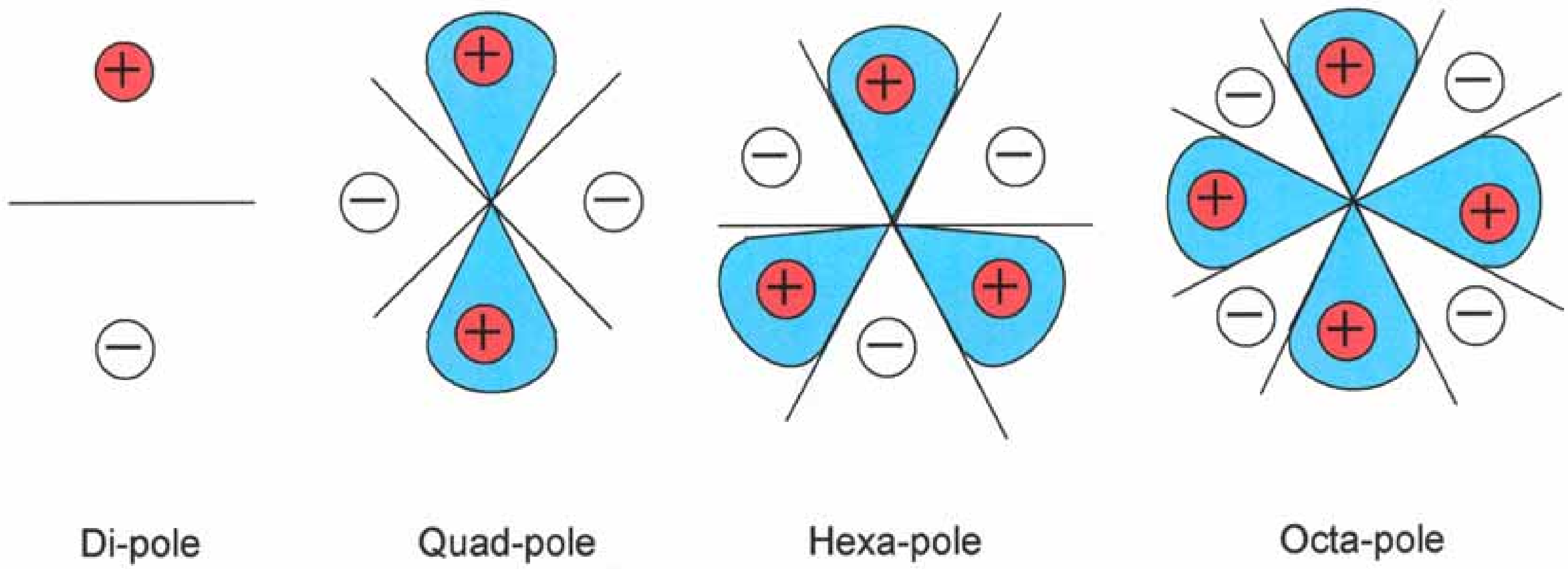


Contributions to probe size at 1keV for C_s, C_c = 5mm d_g=1nm, Schottky emitter

Overcoming aberrations

- **Scherzer showed in 1936 that all normal electron-optical lenses had 'positive definite' aberrations**
- **But later (1947) Scherzer showed that lenses which were not cylindrically symmetrical such as multi-poles, or in which the electron energy changed with time, could have either positive or negative aberration coefficients**
- **Since then many groups have worked to exploit this loophole and produce a compound electron optical lens with reduced aberration coefficients**
- **Hillier and Ramberg's "Stigmator" (1947) was the first example - using a multi-pole (weak quadrupole) device used to correct the geometrical aberration that produces astigmatism**

Choice of Corrector Symmetry



Di-pole:	Alignment of electron probe
Quad-pole:	Correction of Chromatic aberration
Octa-pole:	Correction of Spherical aberration
Hexa-pole:	Correction of aberration caused by the above poles

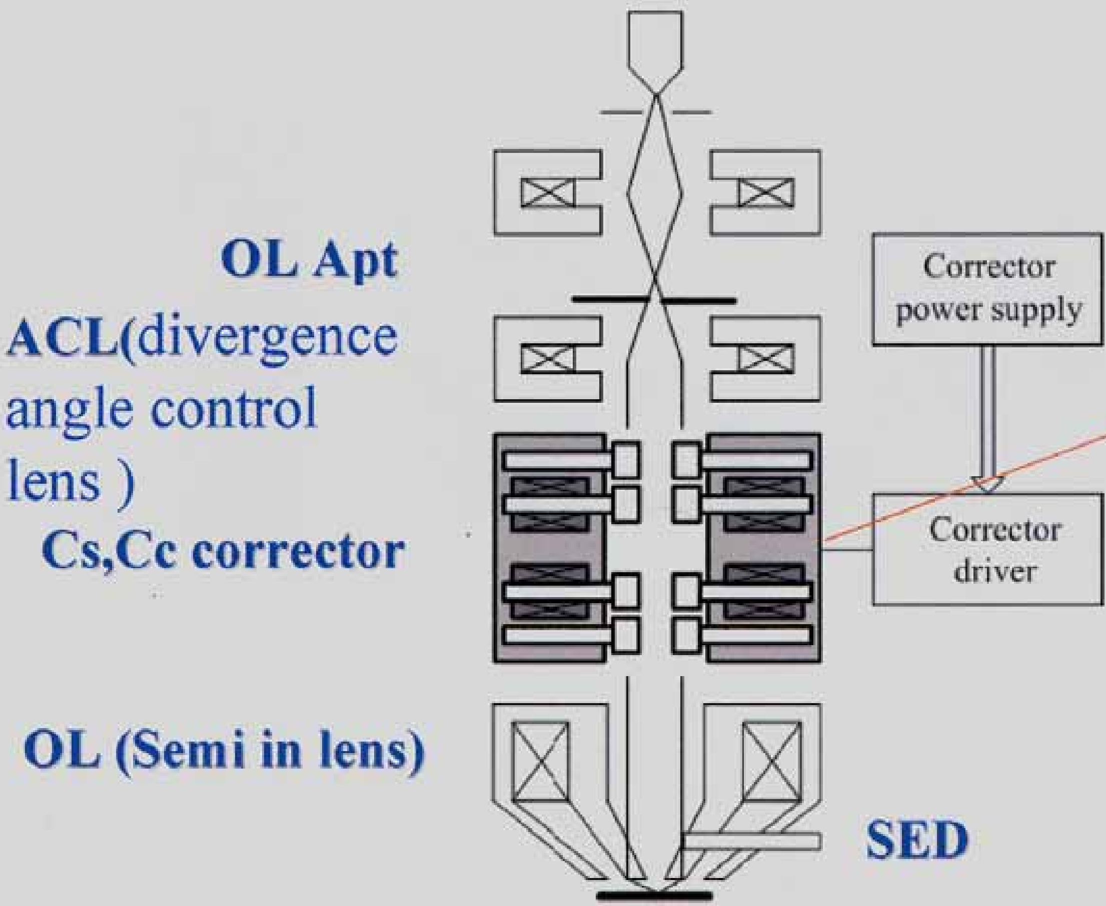
Each of four correctors function as combination of above poles.

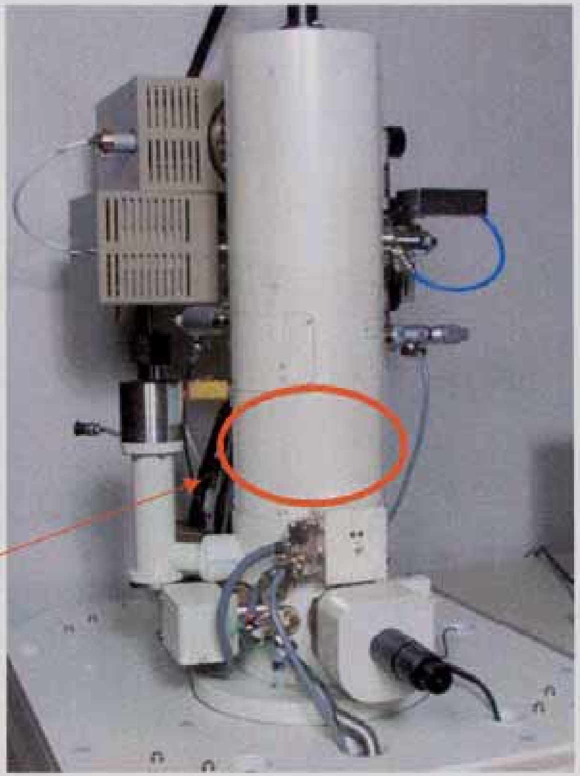
The aberration corrected SEM

JEOL 7700F –
1st commercial AC-SEM

- **The first examples of an Aberration Corrected SEM (ACSEM) are now available commercially (JEOL) using a CEOS corrector**
- **This uses a stack of multi-poles to control chromatic and spherical aberration**
- **The increase in NA that is then possible also removes diffraction as a limit**

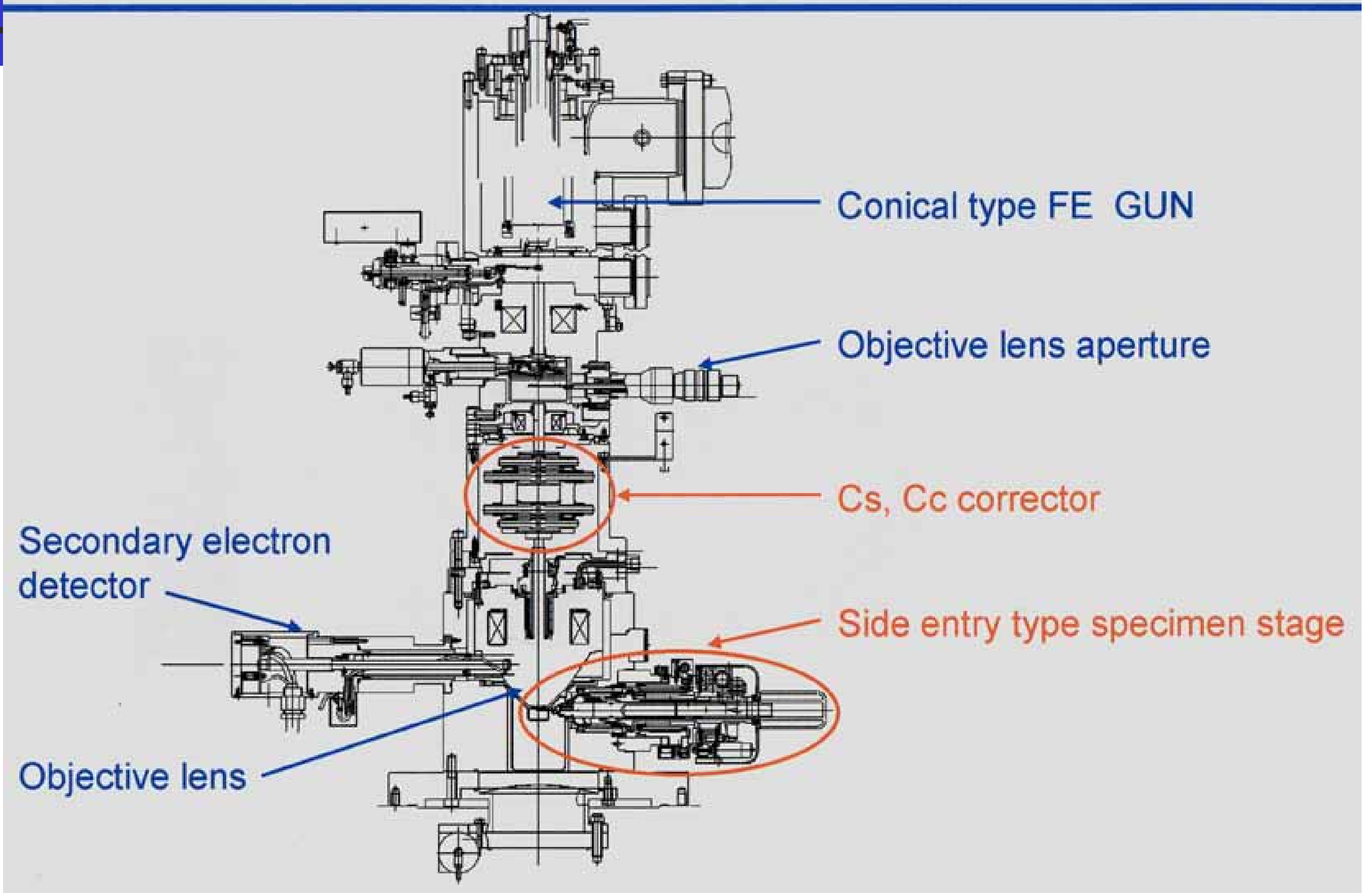
Electron-Optics of 7700F



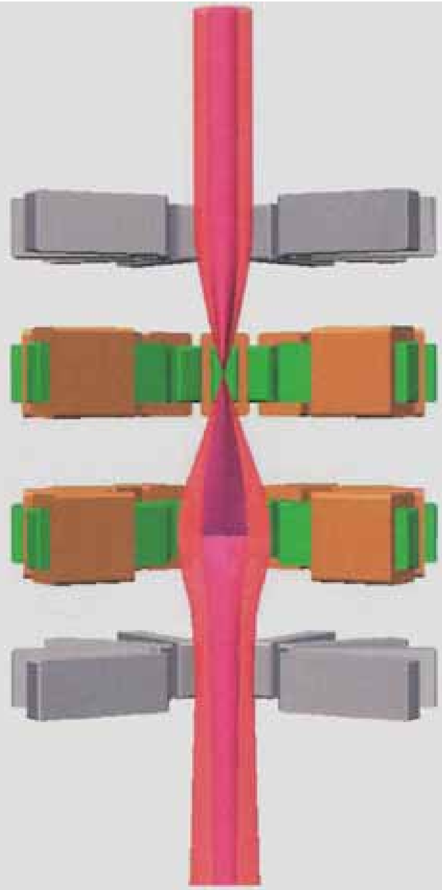


Collimated beam through the corrector is desirable and reduces Boersch effect

Cross-section 7700F

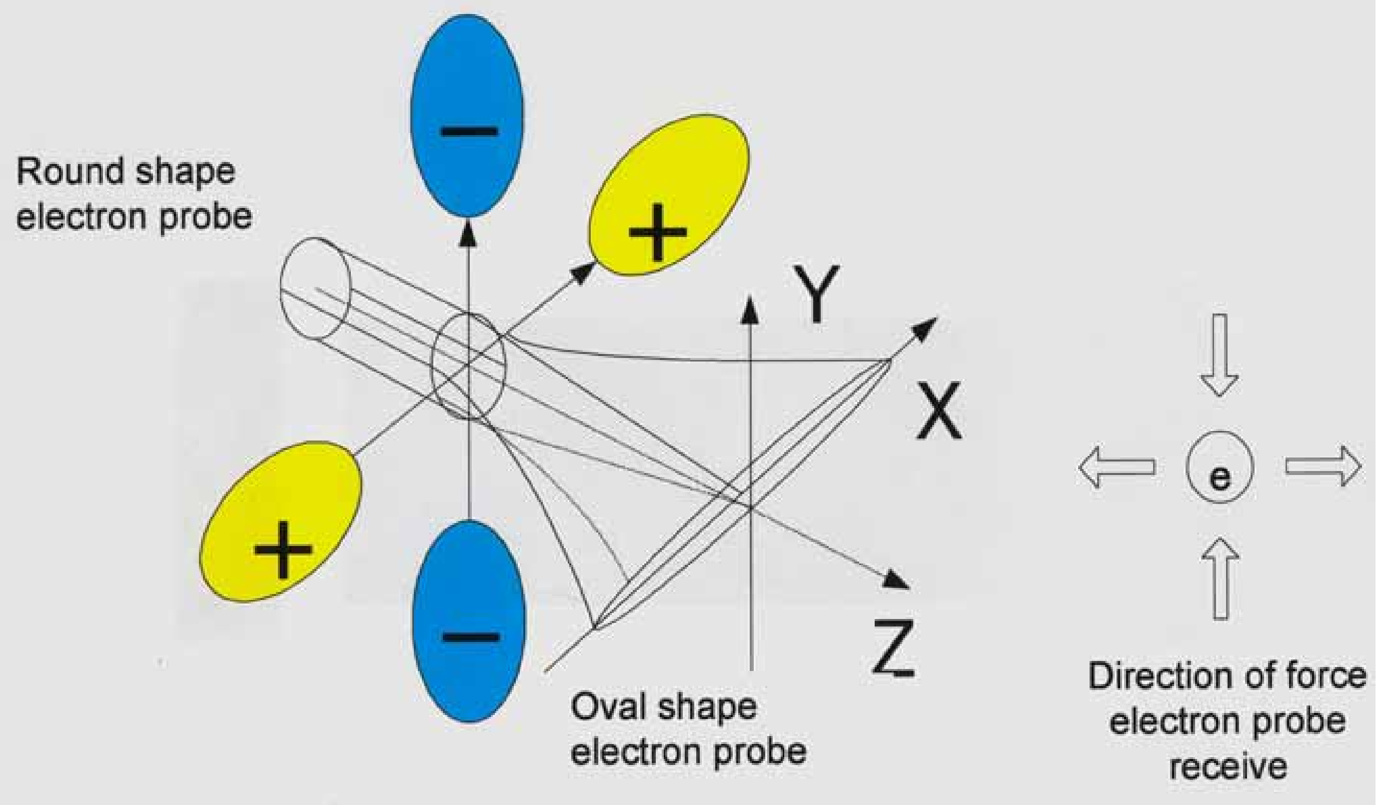


CEOS corrector



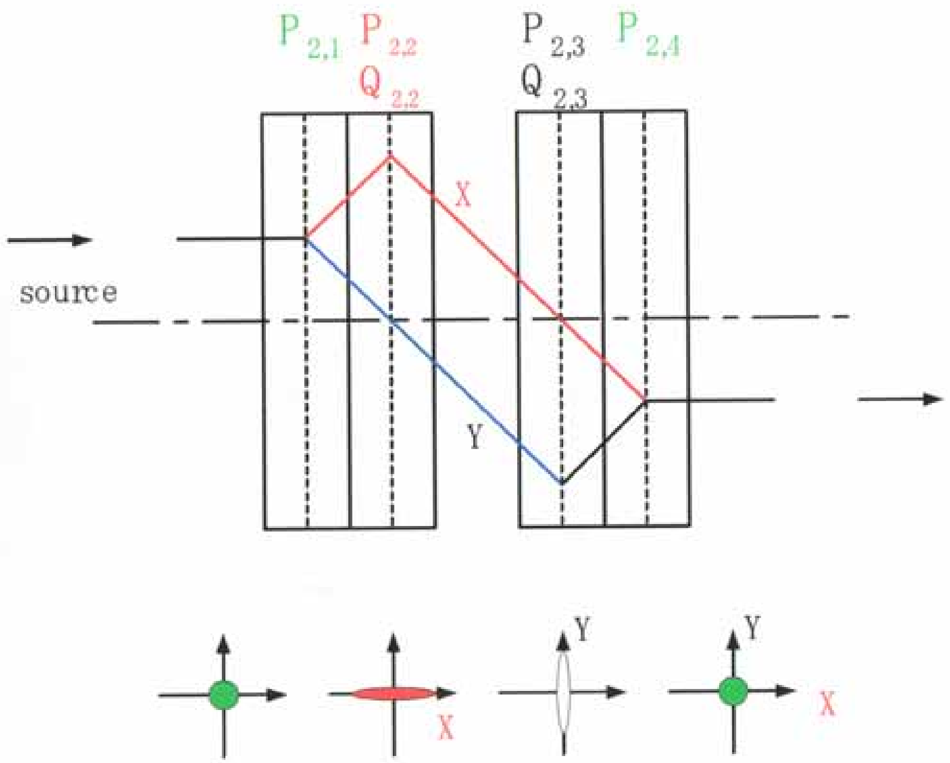
The X and Y components of electron trajectory are corrected independently to cancel the aberration of objective lens.

Operation of Cc Corrector



The quadruple pole corrector forms elongated electron probe.

Trajectories through Cs corrector



The X and Y components of electron trajectory are corrected independently to cancel the aberration of objective lens.

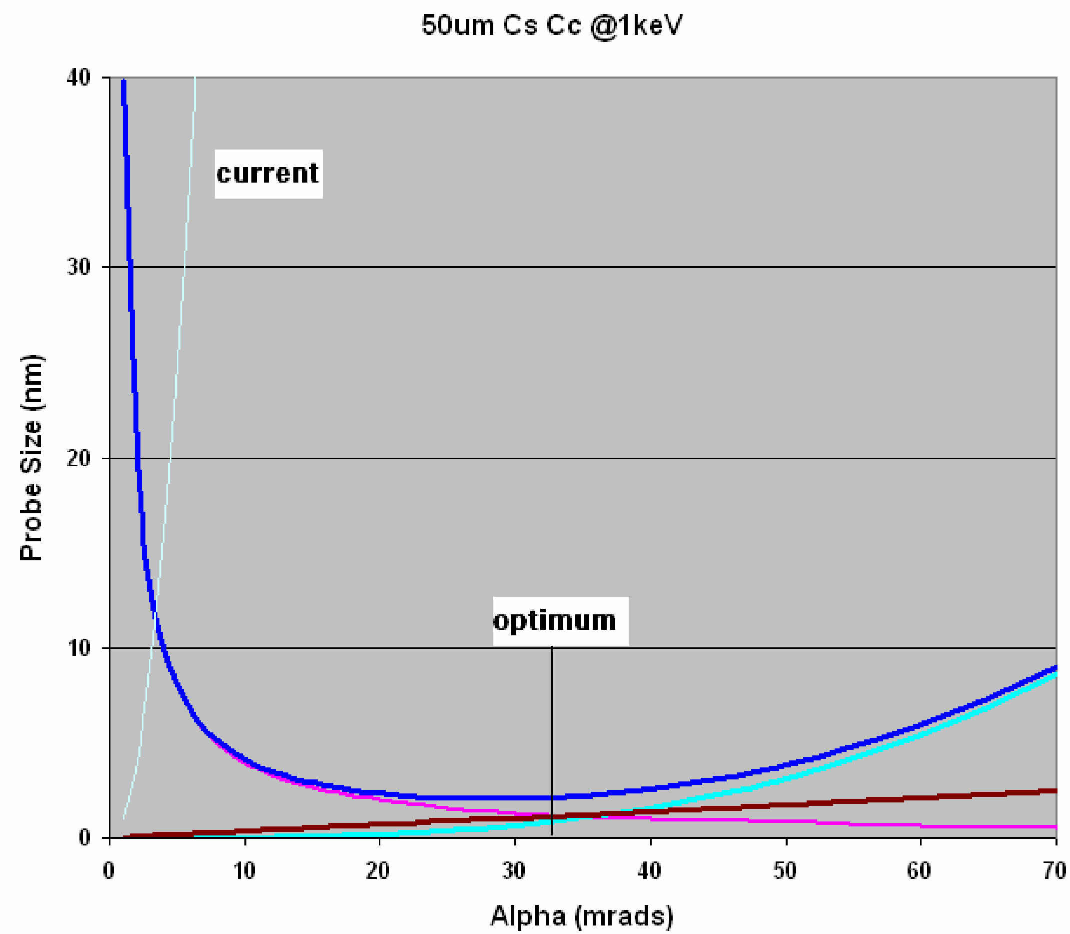
Applying Aberration Correction

✓The minimum probe size falls from 18nm to 2nm

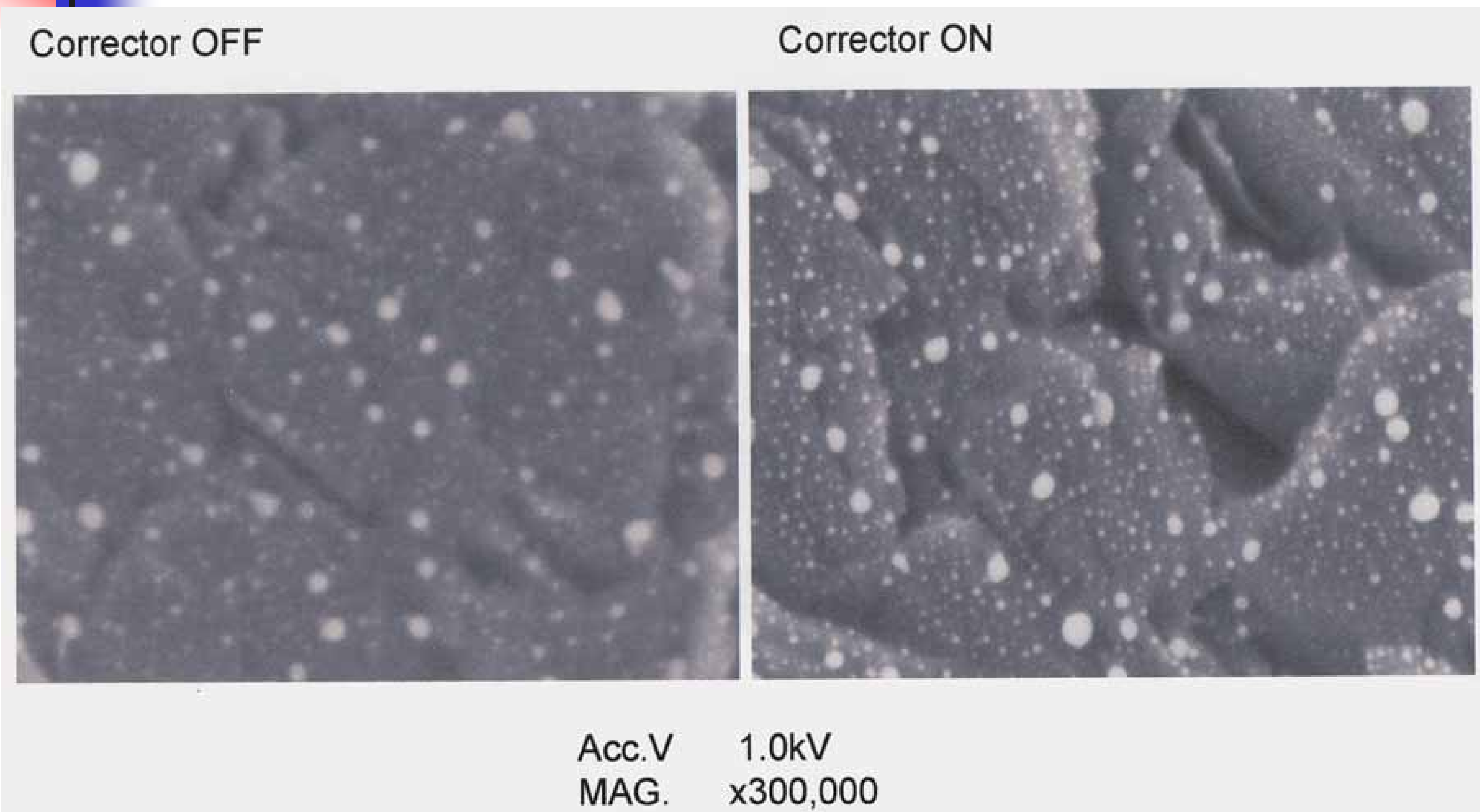
✓The optimum numerical aperture of the lens increases so diffraction limiting is minimized

✓The current in the probe rises by more than 30x

✓The properties of the lens are no longer determined by the working distance so there is much more freedom in designing the sample area

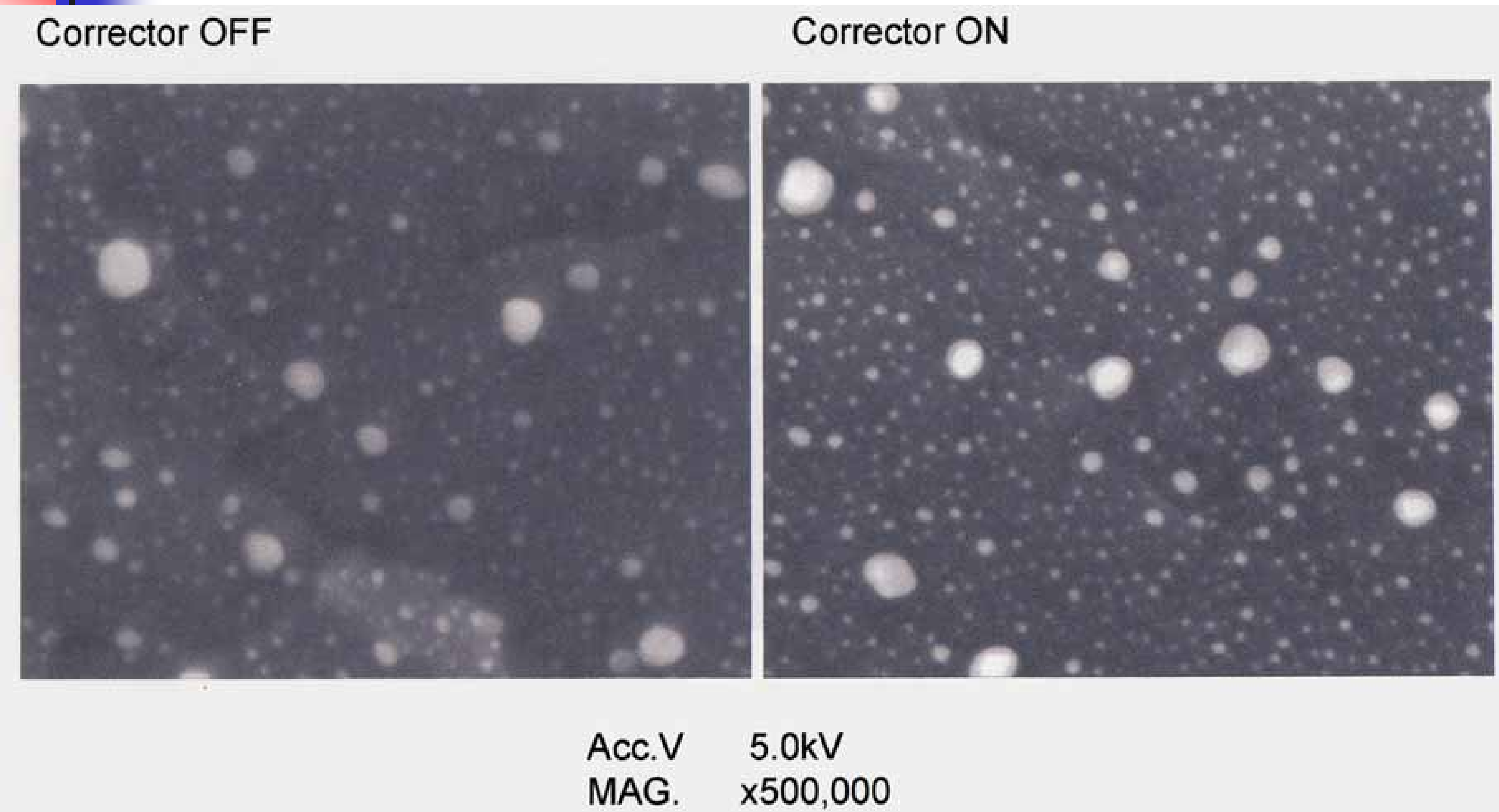


Operation at 1keV



Courtesy JEOL USA

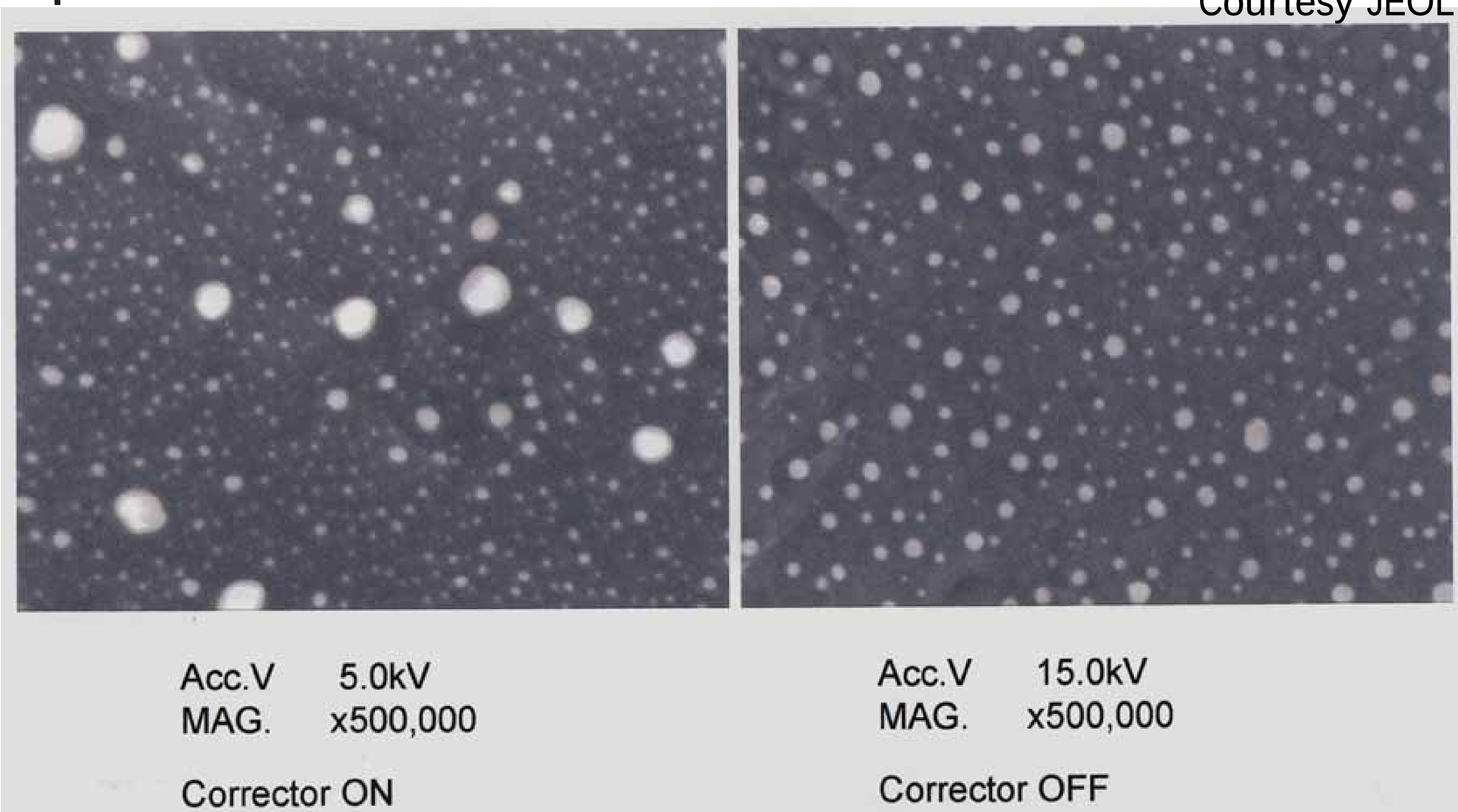
Operation at 5keV



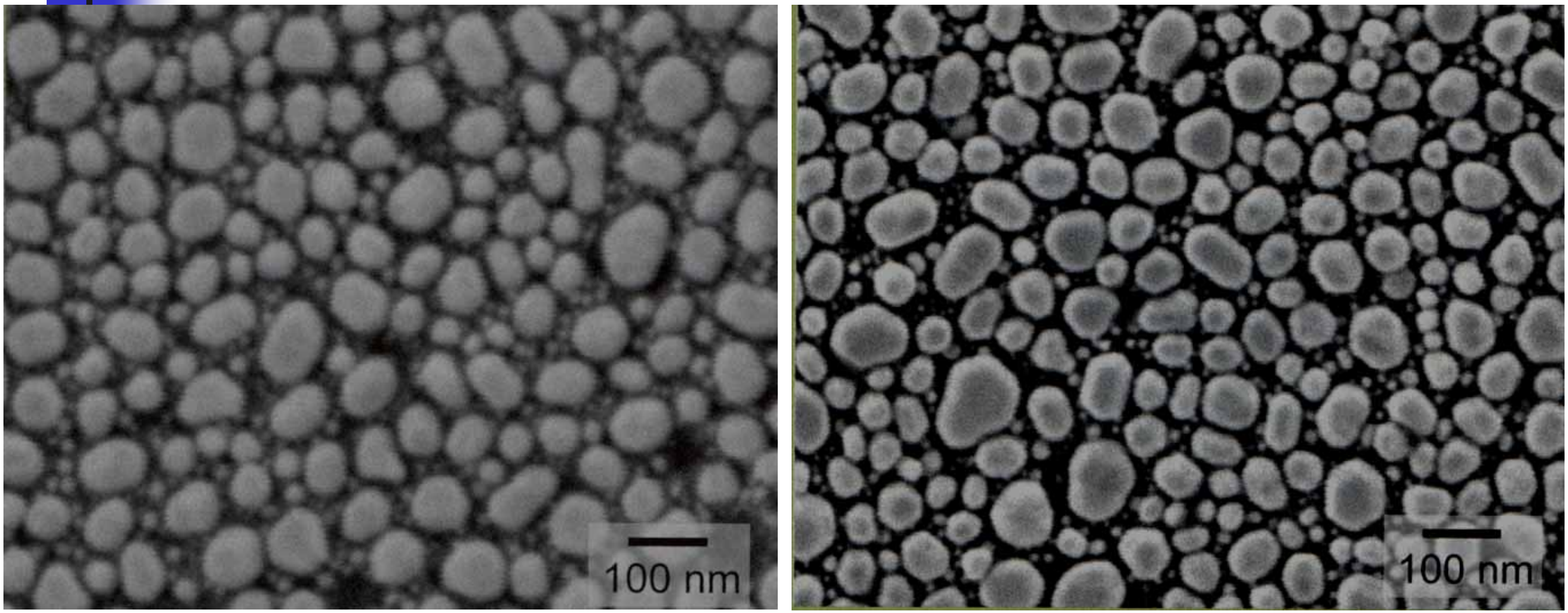
Courtesy JEOL USA

Is 5kev as good as 15keV?

Courtesy JEOL



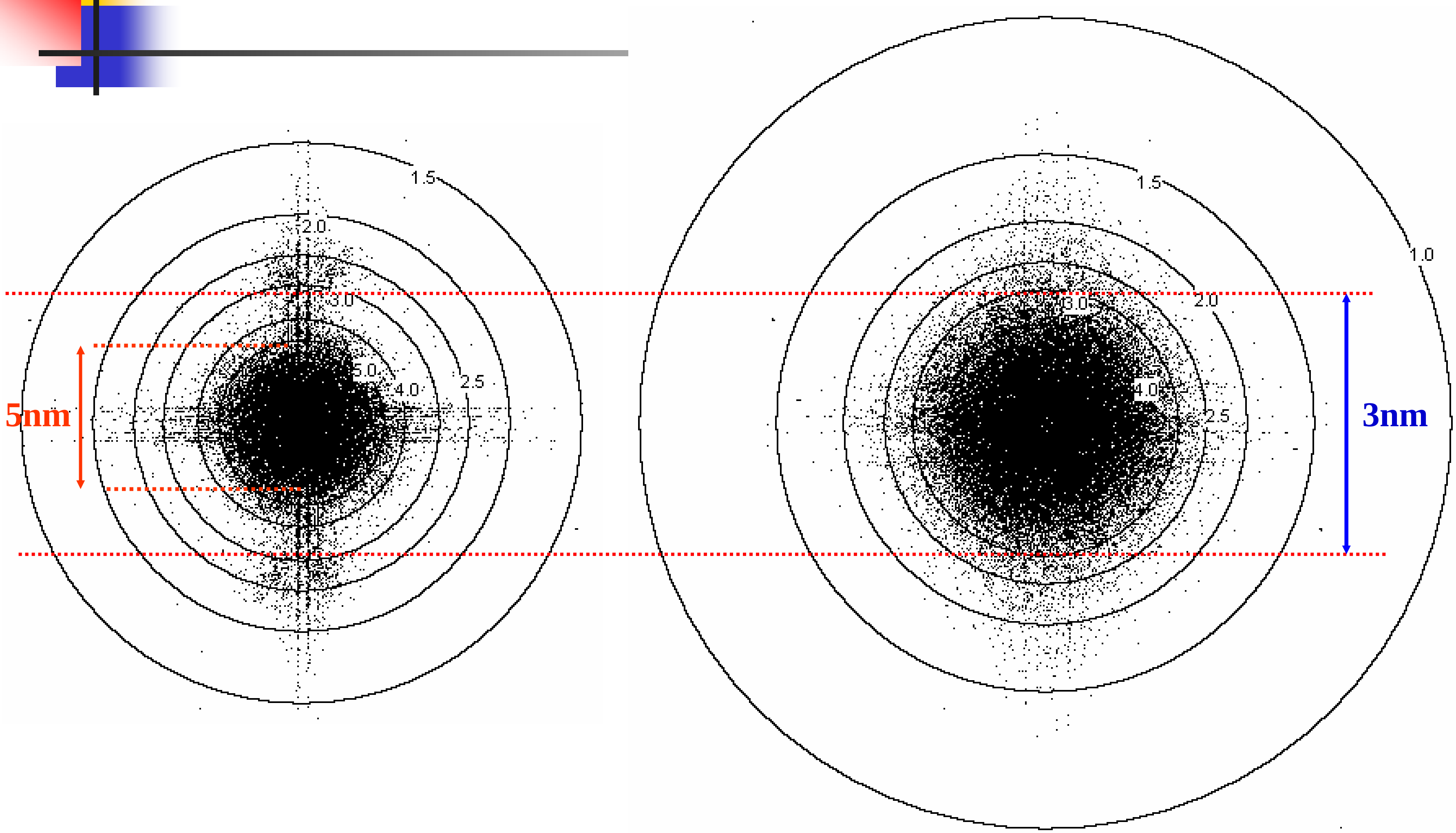
Measuring the improvement



Uncorrected (left) and Corrected (right) images from JEOL 7555S LSI inspection SEM at 1keV and a WD of 4mm. The effective Cs and Cc values after correction are of the order of microns and the aperture is approximately 40 milli-rads.

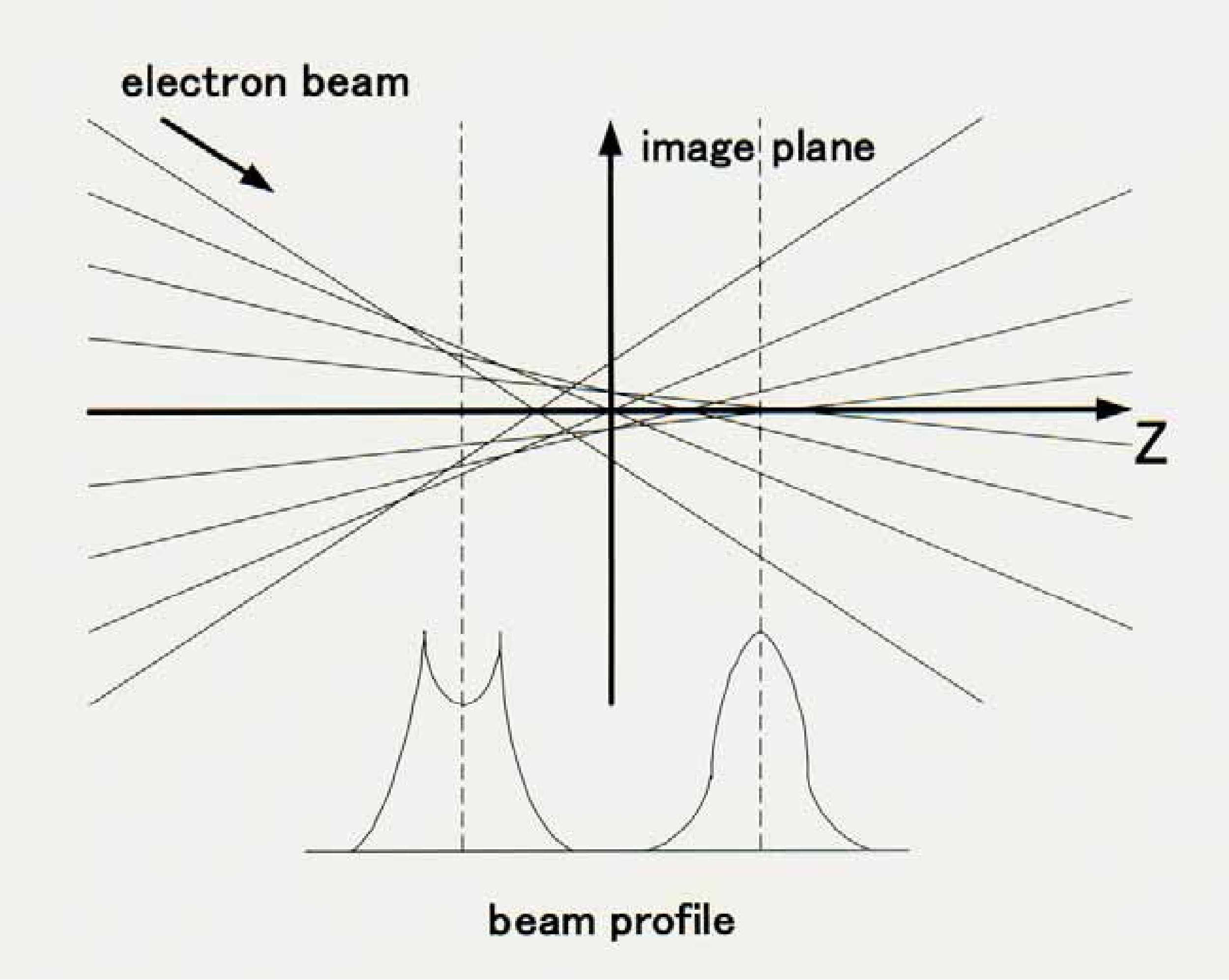
Courtesy JEOL USA

SMART analysis of ACSEM



Correctors off **Correctors On**

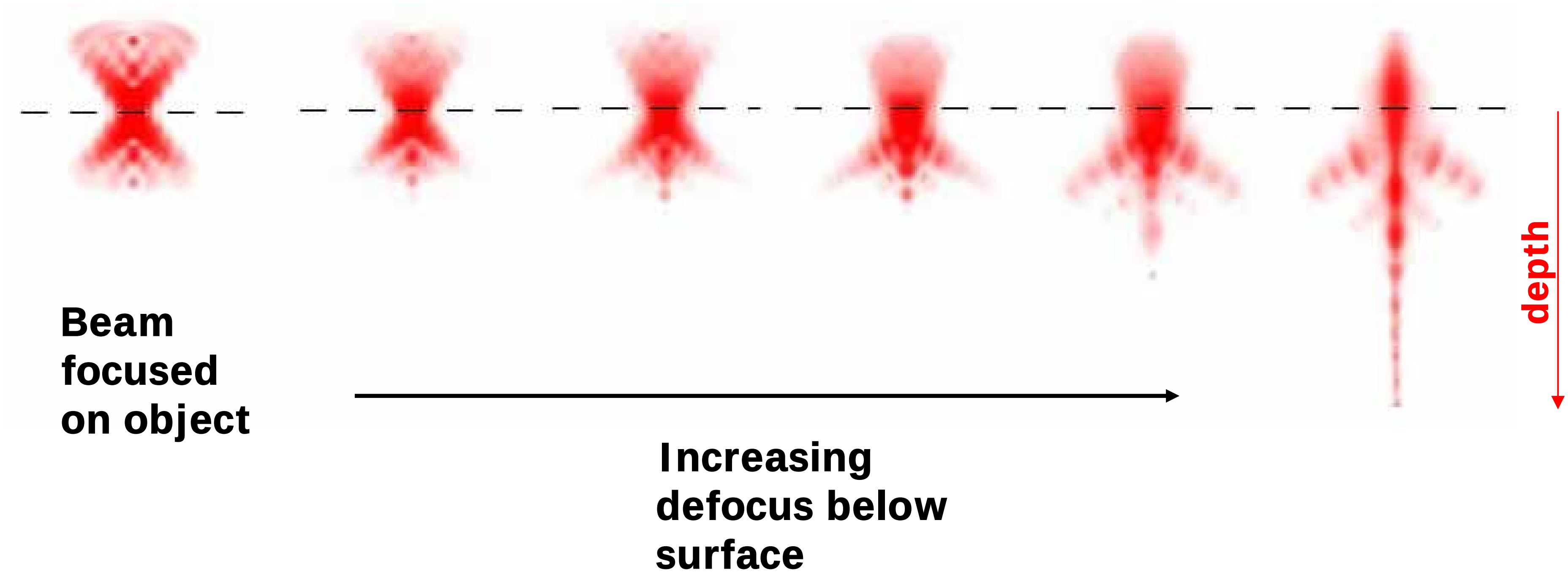
Less aberrations – other benefits



With aberrations the beam profile changes rapidly through the focus

PSF Depth of Field and Spherical Aberrations

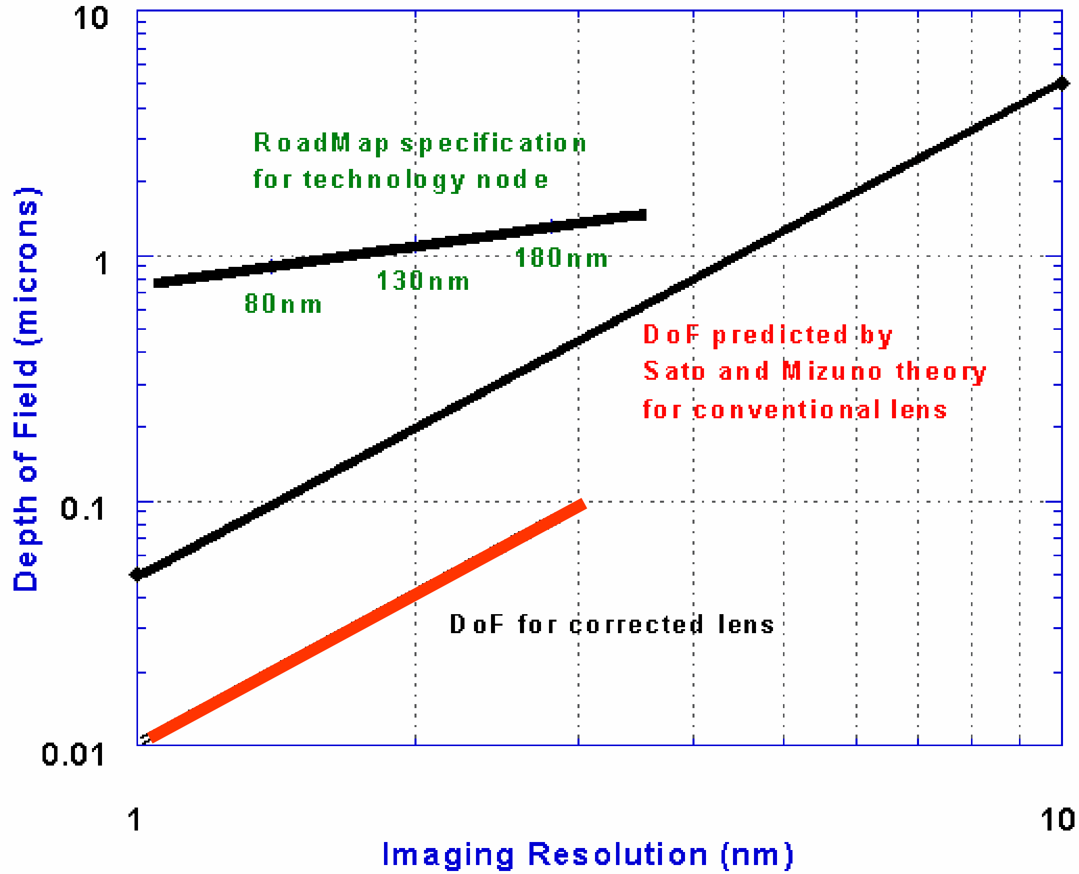
Courtesy Olympus USA



In the ACSEM the PSF of the defocused beam does not change –focus is less critical and profiles will be more interpretable

But we have a new problem

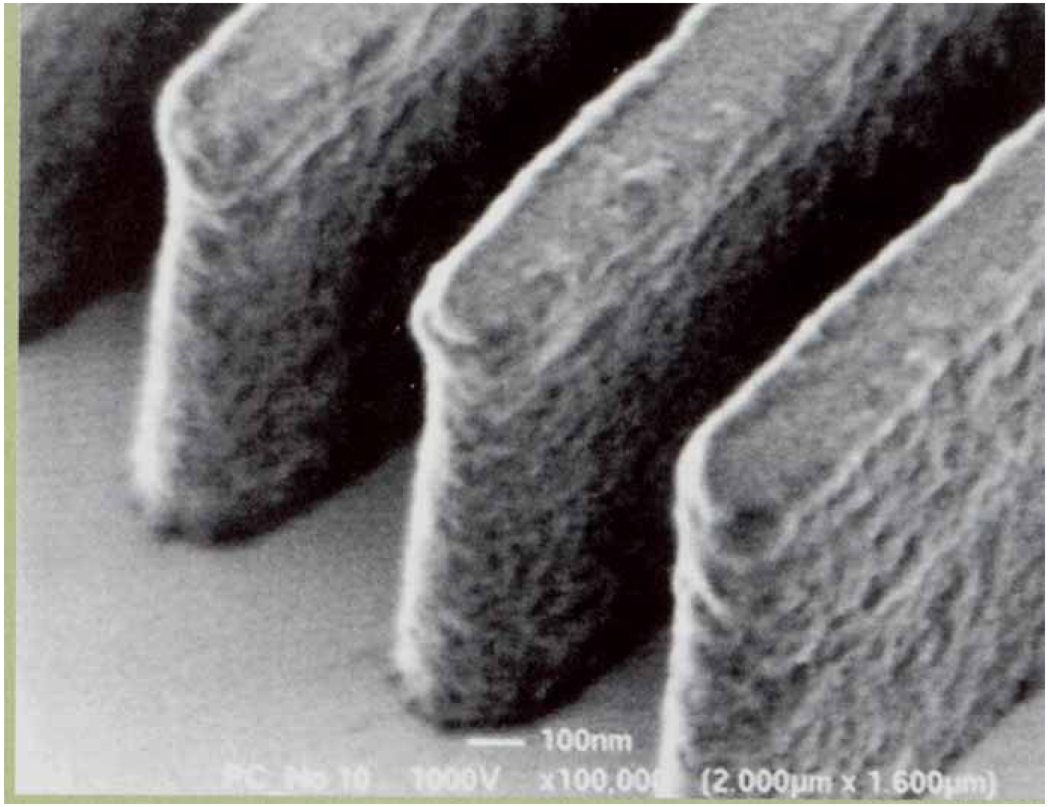
- **The image depth of field depends on the pixel size divided by the NA of the lens**
- **Even with present lenses the DoF is too small for comfort**
- **In the ACSEM the resolution is higher so the pixel size is smaller, and the NA has also been increased significantly**
- **The depth of field is thus correspondingly much smaller than in an uncorrected tool**



Adapted from M Sato, F Mizuno, EIPBN 2000

Depth of Field effects

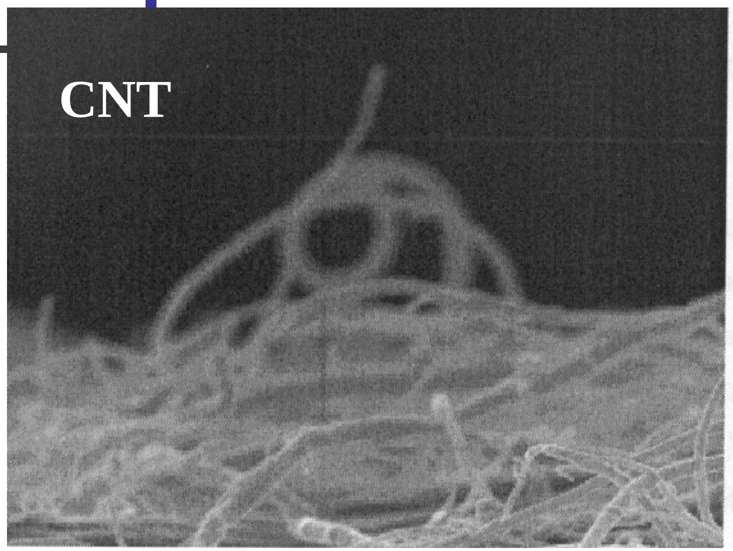
- **This effect is evident in images from the 7700F where even at modest (x100k) magnifications the reduction in Depth of Field is clearly visible top to bottom across the features**
- **But note that - as shown above - the NA of the ACSEM can be varied over a 4:1 range without greatly changing the probe size, so DoF can be enhanced by trading away beam current**

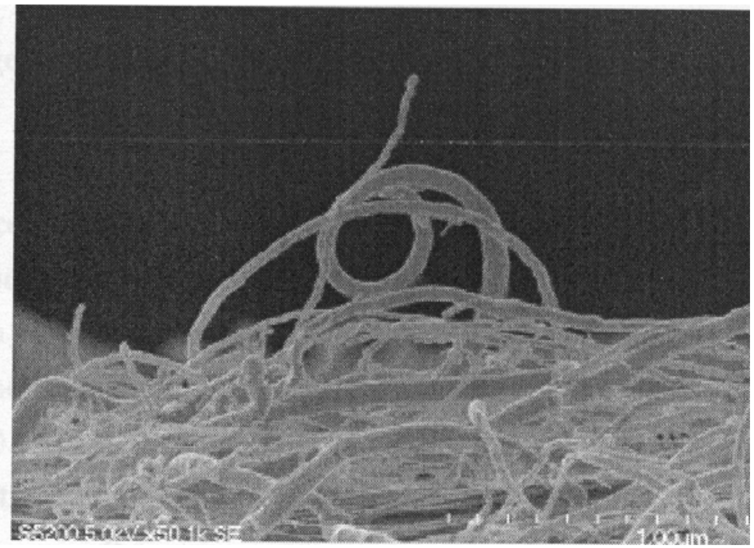


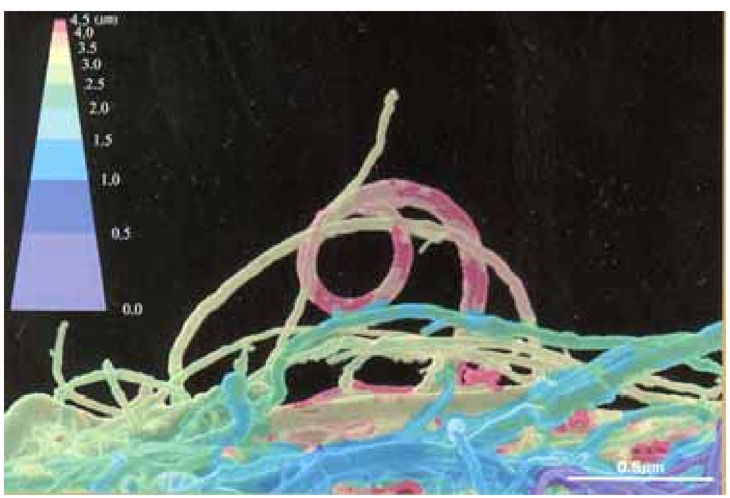
45 degree tilt image from JEOL 7700F

Courtesy JEOL USA

Depth of Field





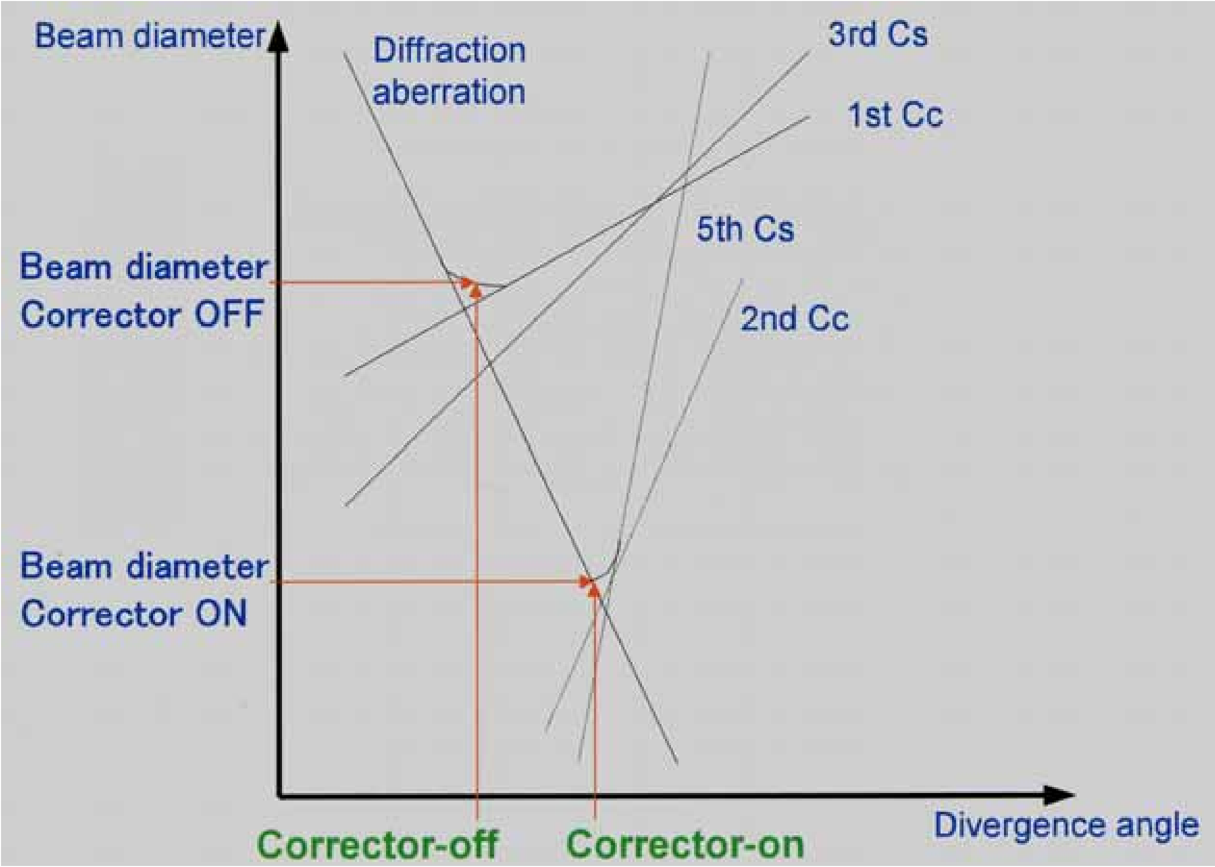


- **With high aspect ratio structures Depth of Field is an important parameter. Compensating for a limited depth of field by through focal reconstruction is possible but requires multiple exposures and careful alignment**

What happens next ?

With the present system we will now limited by higher order (5^{th} order Cs and 2^{nd} order Cc) aberrations

Canceling these would permit a still better probe size and shape, more current and a larger NA but the improvement may not yet be worth the effort



Final points on the AC CD-SEM

- **Aberration correction is expensive adding $500k per column to the base cost**
- **Aberration correctors require exact set-up and may require frequent adjustments. Although automated these operations are non-trivial and the algorithms required to perform it on the ACSEM are not as rugged as those for TEM and STEM and suitable targets are absent**
- **Aberration correction does not only benefit high resolution instruments . . . .**

Other candidate for AC

- **Analytical SEMs – aberration correction would give a major increase in beam current (without an increase in probe size) for improved chemical sensitivity, and allow better access below the lens for X-ray detectors**
- **Defect detection tools would benefit from higher reading speeds and lower error rates**
- **Electron beam lithography tools would have higher writing speeds and smaller probes without the need to upgrade electron sources**

Acknowledgements

- **To Charlie Nielsen (JEOL USA) for his help in providing the experimental data and for permission to show the results originally published in JEOL News**
- **To Prof. Harald Rose for developing the practical aberration corrector, and to Larry Allard, Steve Pennycook, Edgar Volkl (ORNL) for valuable discussions and insights on aberration correction**

The importance of OTF

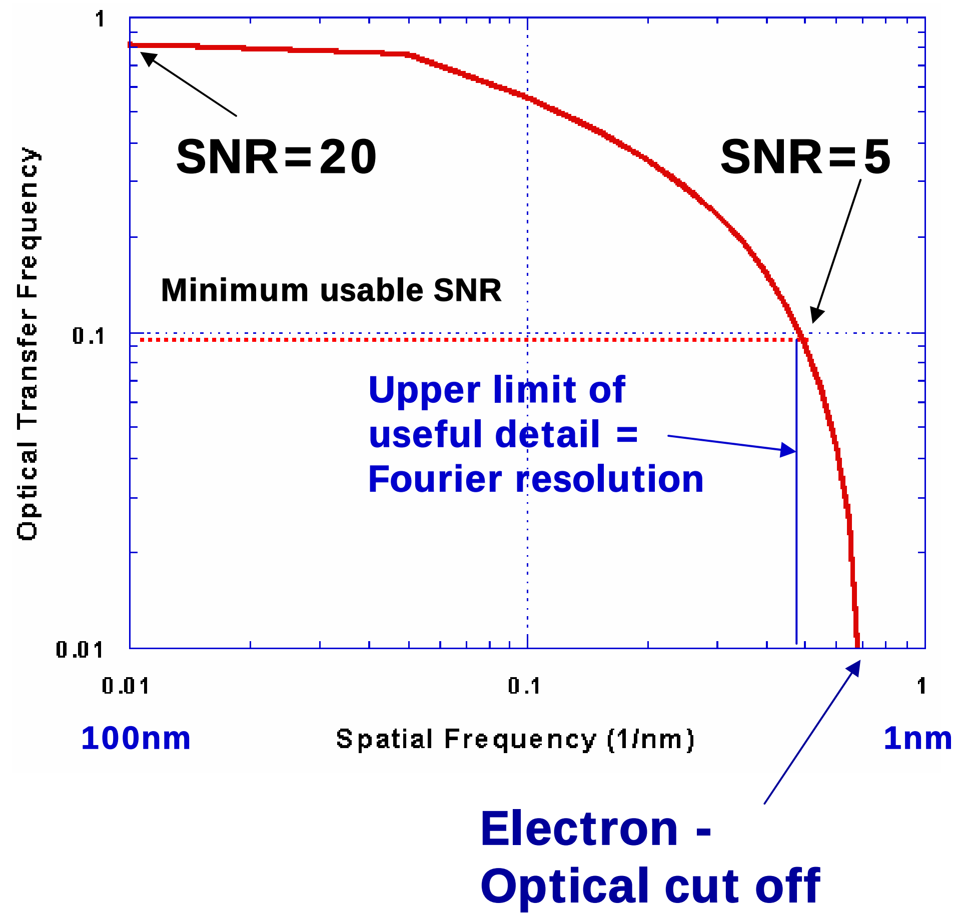
- Describing SEM performance only in terms of its probe size and current is simplistic and unrealistic
- More insight can be gained by considering the Optical Transfer Function (OTF). This describes the properties of the Fourier filter represented by the SEM and hence which spatial frequencies ω of the image are transferred. A low value of OTF(ω) at any frequency results in a loss of information and a possible distortion in the profile.
- If the Signal to Noise ratio for a static beam is SNR(0) then at a spatial frequency ω then SNR becomes

$$SNR^2(\omega) = SNR^2(0).OTF(\omega)$$

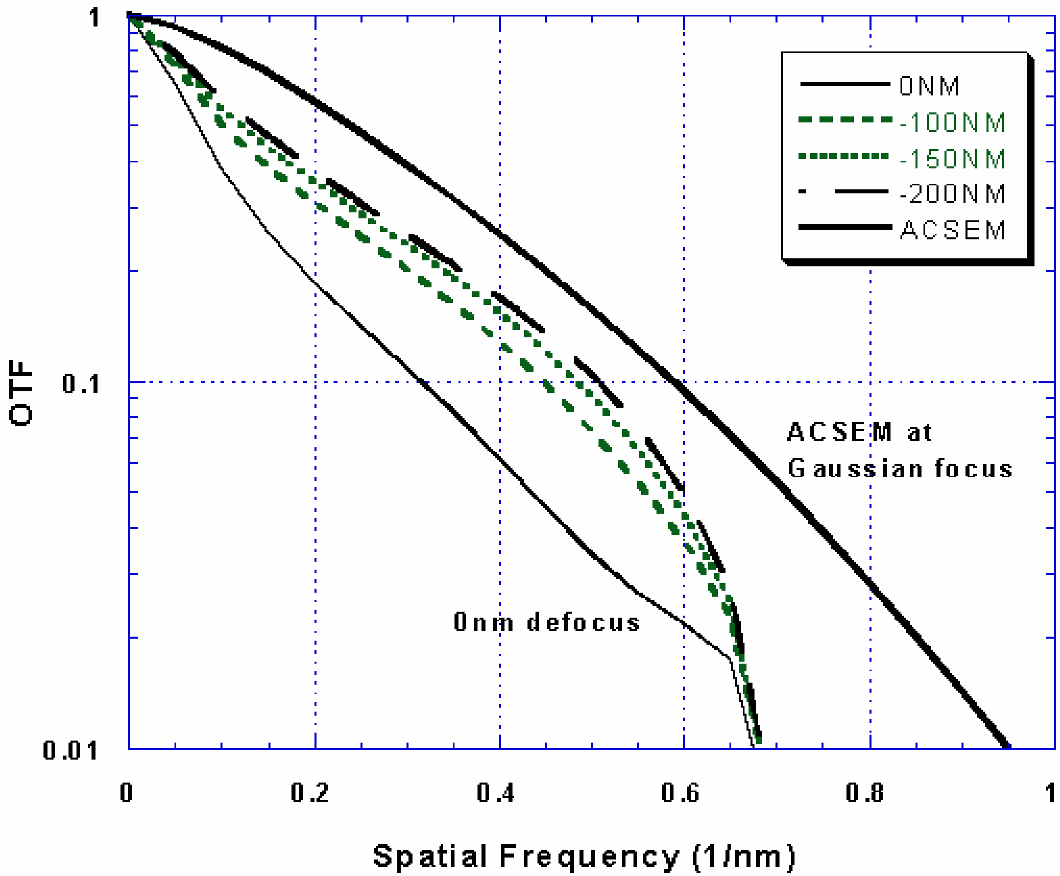
- OTF data provides an overview of all of the characteristics of the tool and facilitates meaningful comparisons

OTF, SNR and resolution

- **For a given SNR(0) the OTF determines the highest spatial frequency at which statistically meaningful data is obtained. This is the true resolution limit of the tool and depends on the SNR**
- **The low beam currents that accompany low beam energies directly result in a degradation of resolution**



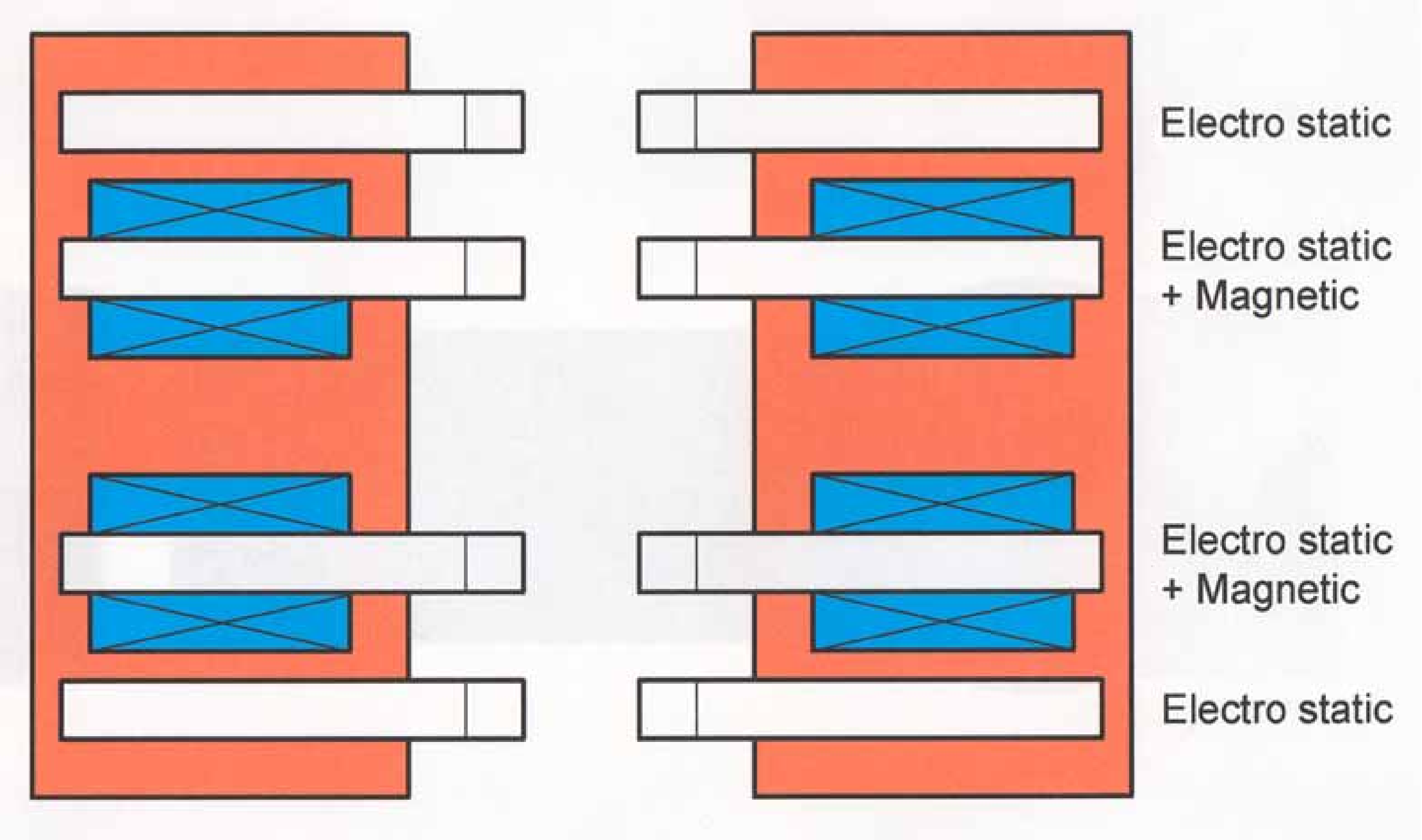
The ACSEM advantage in OTF



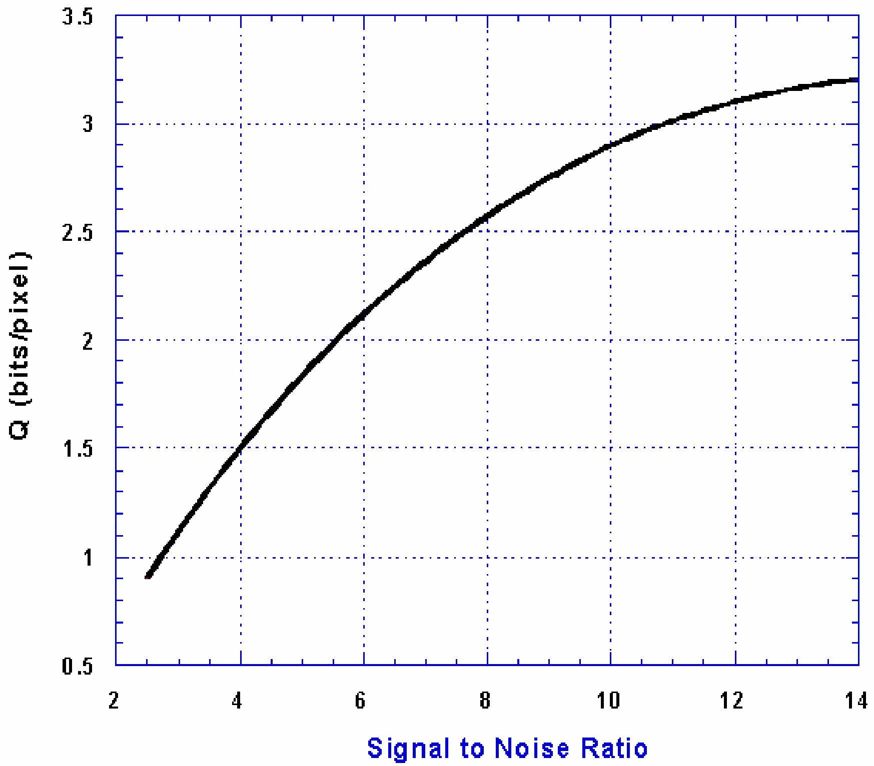
Computed OTF data at 1keV with/without Aberration Correction

- OTF and SNR is improved at all spatial frequencies in the ACSEM– not just at the resolution limit
- In a conventional SEM the OTF varies with focus because aberrations give rapid changes in the beam profile. A focus change of 50nm is enough to change the effective resolution limit by a factor of 2x
- In the ACSEM is obtained at Gaussian focus – not at some arbitrary defocus. Should guarantee better data reproducibility in metrology

Layout of CEOS corrector



The Digital Significance of SNR



- **Although SNR is an 'analog' concept it is very relevant to digital instrumentation**
- **Using Shannon's theory Simon (1970) showed that the data passing capacity of the SEM vs SNR has the form**

$$B_{\text{bits/pixel}} = \log_e \upsilon^{1/2} - \frac{\exp(-\upsilon)}{\upsilon^{1/2}} + \frac{erf(\upsilon)}{\upsilon^2}$$

$$\text{where} \quad \upsilon = \frac{\text{normalizing constant}}{\text{SNR}^2}$$

Plot (after Simon 1970) of channel capacity vs SNR

Shows that the digital depth of the data is low (<4 bits) at typical SNR