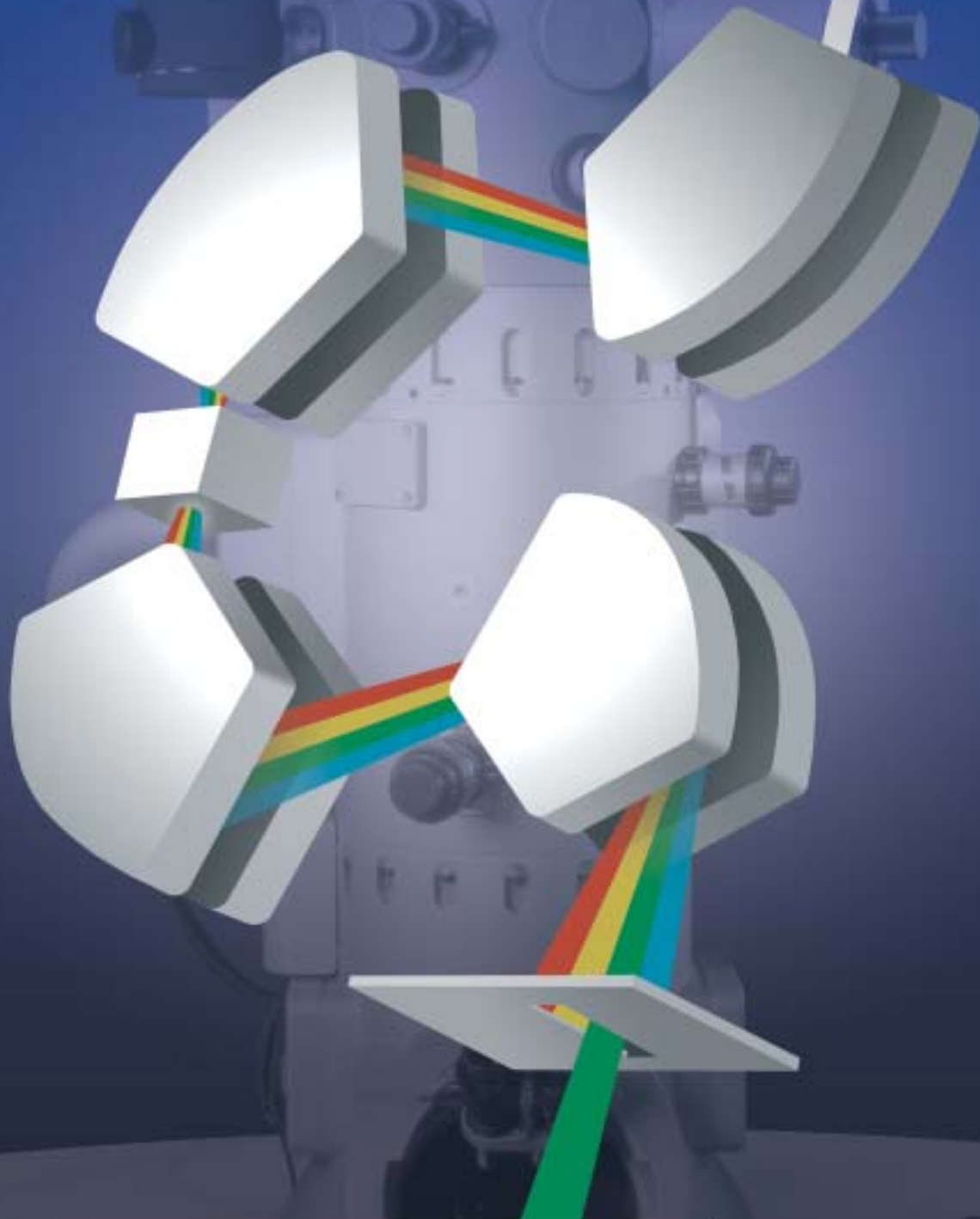


In-column EFTEM Technology with Corrected OMEGA Filter



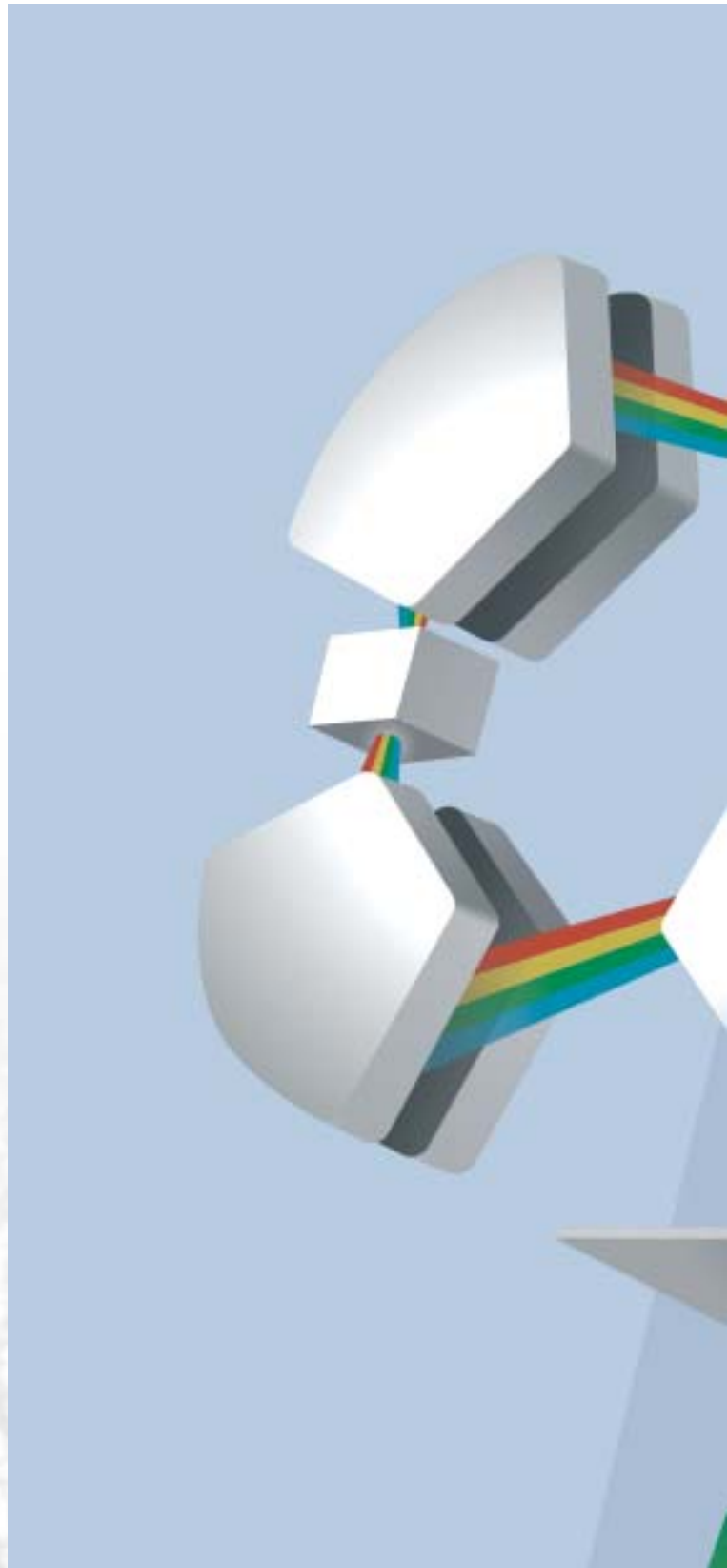
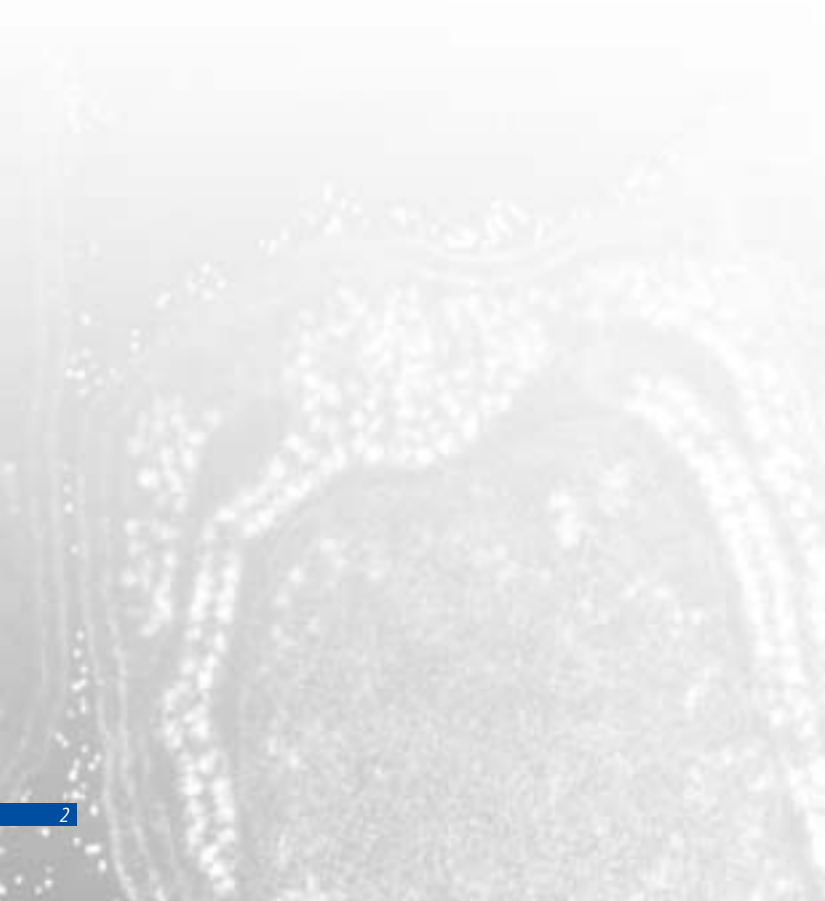
Limits of conventional transmission electron microscopes and how to overcome

Conventional transmission electron microscopes (CTEM) of state-of-the-art design differ from previous models in that they are computerised, simpler to operate and provide higher spatial resolution.

They do not, however, offer any improvement or simplification of the preparational work and the collection of new information for dealing with new challenges.

Essential restrictions in this respect are:

- Limited possibilities for contrast generation or optimisation
- Loss of definition and low contrast when imaging thick specimens
- High time factor and low spatial resolution for element analytical images



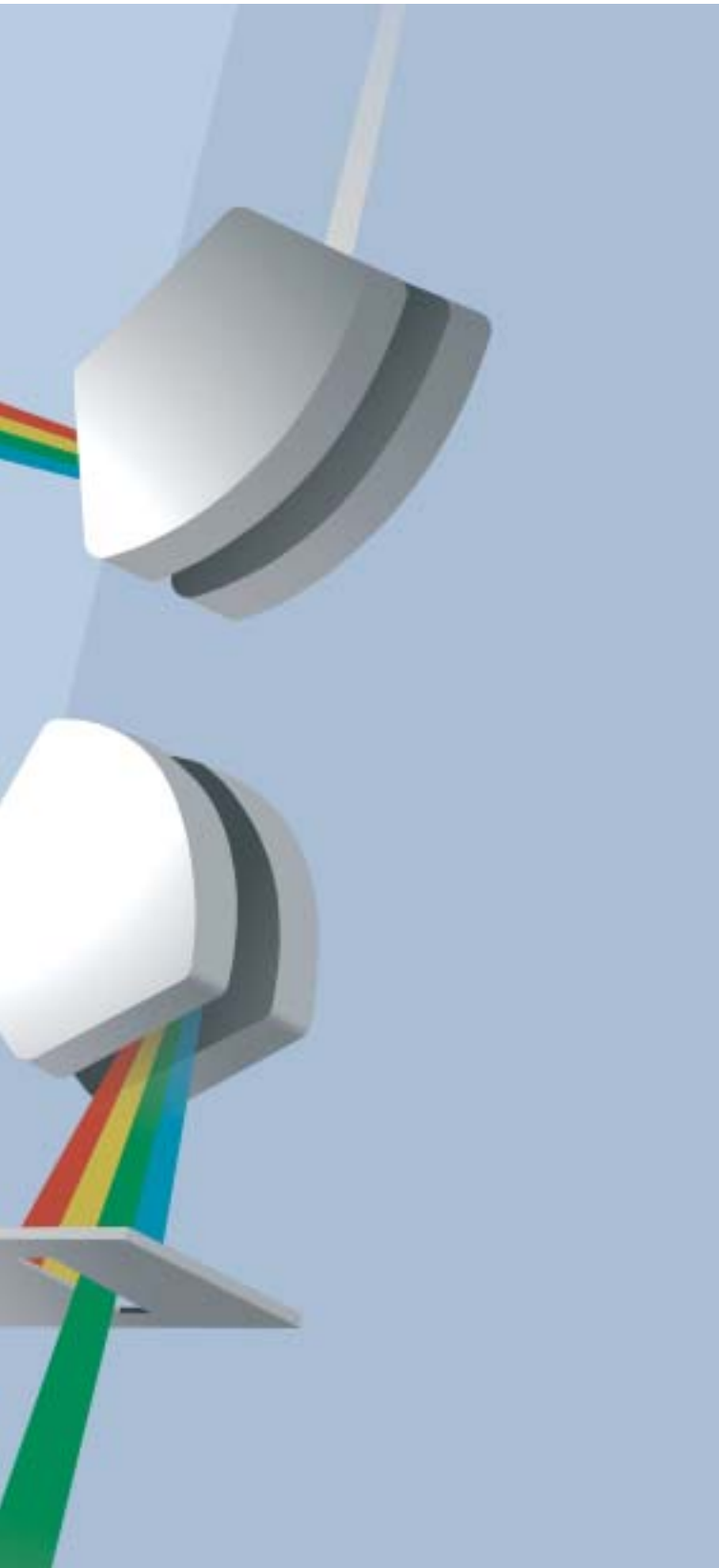
come them

Carl Zeiss SMT EFTEMs

In-column energy filter transmission electron microscopes (EFTEMs) feature a fundamentally redesigned electron optical column with an integrated OMEGA filter as an imaging element.

EFTEMs offer new, additional modes of operation such as elastic imaging, electron spectroscopic imaging, electron spectroscopic diffraction and electron energy loss spectroscopy.

EFTEMs provide all possibilities of CTEMs without any restriction. In addition they also feature unique new benefits which greatly surpass the performance of modern CTEMs and clearly extend their limits.



New EFTEM imaging and analysing modes and the benefits of their application

Electron spectroscopic imaging with elastic electron scattering

- Higher contrast without any loss of resolution in the imaging of all types of specimens.
- Sharply defined, high contrast images even with thick specimens.



Elastic, convergent diffraction image (large angle CBED) of an aluminium specimen with [111] orientation.

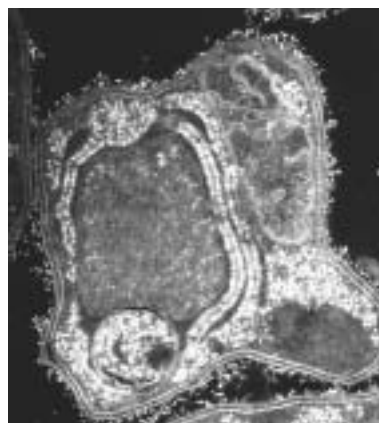
Specimen courtesy of Prof. J. Mayer, MPI Stuttgart, now at RWTH Aachen

Electron spectroscopic diffraction with elastic electron scattering (ESD)

- Quantifiable, brilliant diffraction images with enhanced contrast and down to zero-order information.
- Diffraction diagrams with selected energy loss.

Electron spectroscopic imaging with inelastic electron scattering (ESI)

- Higher contrast and improved image quality, especially when imaging thin, unstained specimens.
- New information gained by selective and specific contrast for element distribution images with utmost spatial resolution.

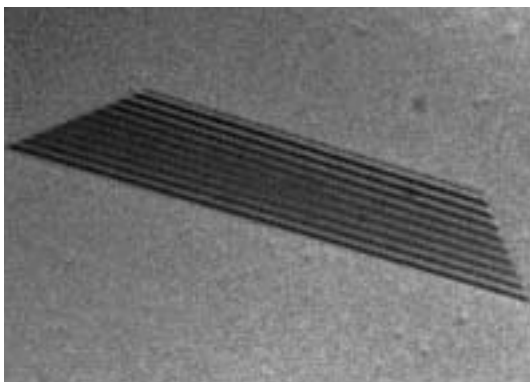


Inelastic image of a biological thin section of 50 nm thickness, with 5 nm immunogold labelling.

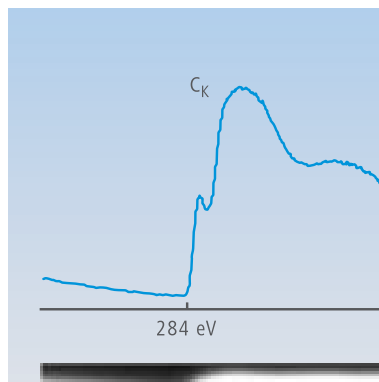
Specimen courtesy of Dr. Dini, Italy

Electron energy loss spectroscopy (EELS)

- Chemical analysis of minute specimen areas for detailed characterisation of the elemental and molecular specimen structure.



Elastic image of a stacking fault. Specimen: Silicon. Specimen thickness: 0.8 μm .



Energy loss spectrum with absorption edge (K-edge) of carbon. Below the image from which the spectrum was calculated.

Principle of energy filter transmission electron microscopy

Electron scattering in the specimen is used for image formation in both EFTEM and CTEM. However, EFTEM also utilises additional interactions which are not taken into account in conventional TEM.

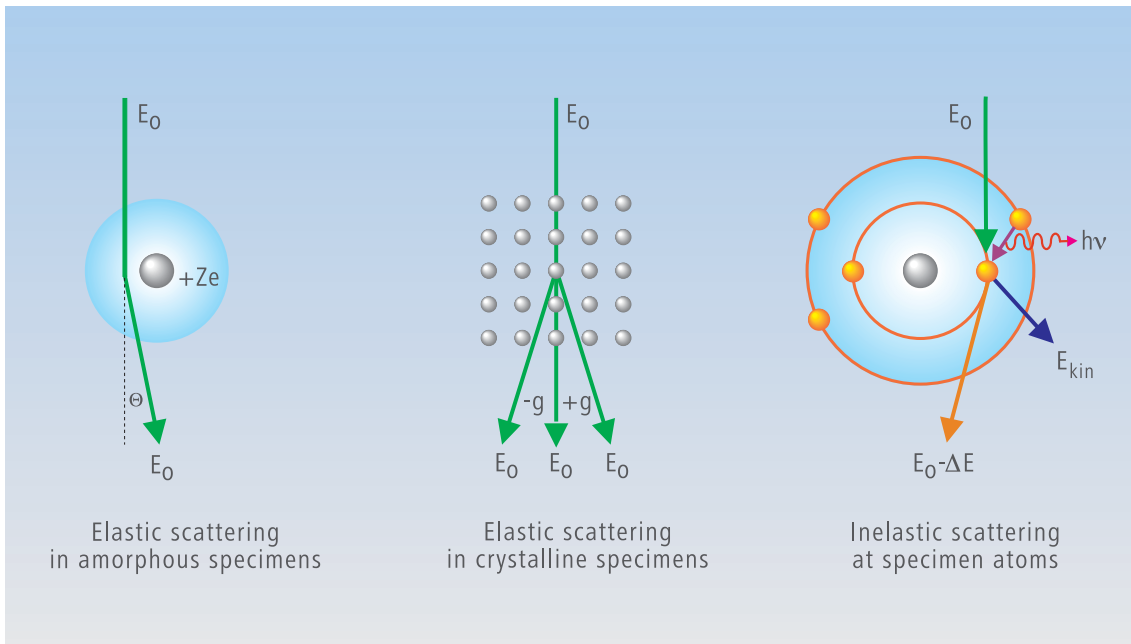
In CTEM, the electrons used for imaging are selected only via the aperture diaphragm according to their scattering angles. Therefore, only electrons with a large scattering angle contribute to contrast generation.

The energy of the electrons and the difference in their energies remain unaccounted for, despite the fact that the bandwidth of the energy differences caused by the chromatic aberration of the objective lens has considerable influence on contrast and resolution.

In EFTEM, the transmitted electrons are not only selected according to their angle, but also to their energy. An energy filter disperses the electrons according to their wavelength or energy. Via a slit of variable width, they are then systematically selected for imaging with an energy loss ΔE and a defined energy bandwidth.

Dual electron selection results in considerably enhanced contrast.

By imaging energy selected electrons, new information can be obtained with contrasts such as the structure and element sensitive contrast. In addition, elemental distribution images with ultimate lateral resolution are possible.



The elastic narrow-angle scattering on the atoms defines the scatter absorption contrast which is used, for example, to image cell structures in biological specimens.

In crystalline materials, the elastic Bragg scattering permits structures and defects to be analysed down to atomic level.

With inelastic interaction, primary electrons change their energy. Due to chromatic aberration, the image contrast deteriorates. Element specific information can only be obtained if use is made of the inelastic scattering processes.

Principle of energy filter transmission electron microscopy

Electron scattering in specimen

During elastic scattering at the specimen atoms, primary electrons with E_0 energy are scattered at large angles Θ without losing any measurable energy.

Inelastically scattered electrons only scatter at small angles, but lose energy and thus change their wavelength. Elastically scattered electrons remain monoenergetic and display an energy bandwidth δE which is largely defined by the cathode. The bandwidth of inelastically scattered electrons, on the other hand, increases dramatically with greater mass and specimen thickness.

Image contrast by electron selection

EFTEM selects electrons not only according to their scattering angle, but also according to energy and energy bandwidth. The conditions for contrast generation are therefore much better than in CTEM, particularly with specimens consisting of light elements.

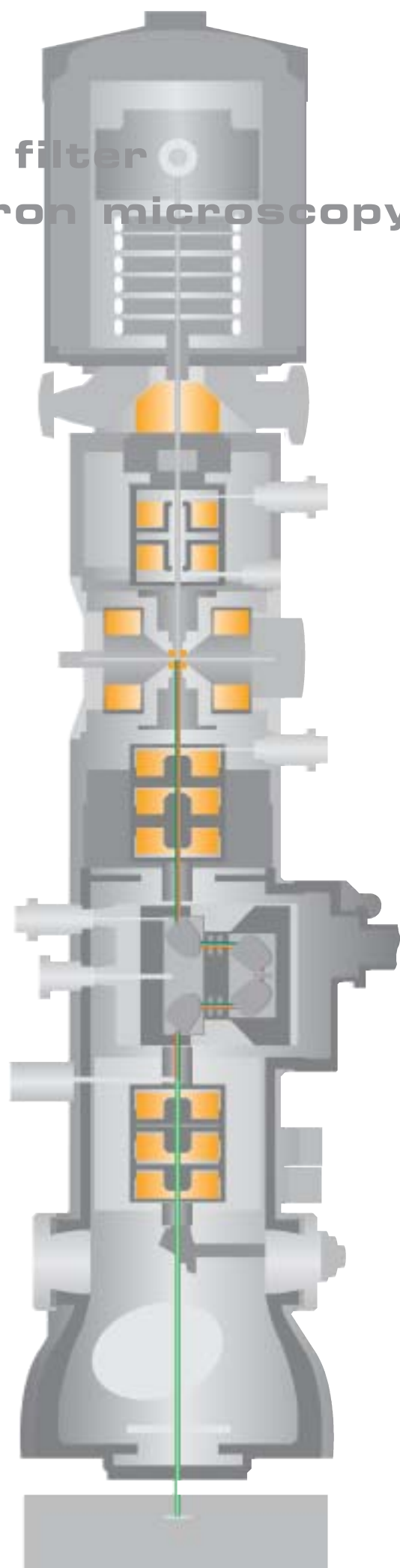
The filtering out according to energy and energy bandwidth does not have an adverse effect on the resolution, unlike smaller lens aperture diaphragms.

Element information of scattered electrons

If specimen atoms are ionised during the inelastic scattering process, energy losses which are characteristic of the element will result. These appear as absorption edges in the energy loss spectrum.

Fine structures in the energy loss spectra carry information on adjacent atoms and permit chemical bonds to be analysed. This makes energy loss analysis ideal for the chemical characterisation of minute specimen structures.

The X-ray quantum $h\nu$ generated during the inelastic scattering process is used for X-ray microanalysis (EDX) both in EFTEM and CTEM.



Electron optical concept of EFTEMs

EFTEMs are innovative electron microscopes featuring state-of-the-art performance for analytical applications, high optical resolution and simple, efficient operation. The instruments are based on a completely redesigned electron optical concept.

Great emphasis was placed, for example, on the correct positioning of the optical cardinal planes of the illumination and imaging systems and of the image-forming spectrometer.

This is essential if the operating parameters of the objective lens and the OMEGA filter are to remain constant in all illumination and imaging modes.

Due to these measures, only one individual lens or a lens system needs to be changed to another default value when the illumination or imaging modes are changed. The time required for handling and alignment by the user is reduced to an absolute minimum.

Illumination system

Flexible Koehler illumination for excellent homogenous wide-field illumination in TEM operation, spot illumination for analysis and scanning operation with discrete control of brightness and illuminated field size, and ideal optical conditions for all types of diffraction.

Objective lens

Symmetrical Riecke/Ruska-type condenser/objective lens with spatially defined positions of the first diffraction image and the intermediate image.

First projector system

Three-lens magnification system for imaging the first intermediate image or the diffraction image in the fixed entrance plane of the subsequent energy filter.

Energy filter

Imaging OMEGA energy filter which supplies an achromatic image of its entrance image plane, and at the same time produces a spectrally dispersed image of its entrance aperture (energy loss spectrum), from which the required energy range can be selected using the analysing slit aperture.

Second projector system

Magnification system for optional imaging of the filtered image, the diffraction image or the energy loss spectrum on the screen or by different detectors, featuring variable magnification for optimum matching to detector size.



Design and function of electron optics

Electron optical design of EFTEMs with illumination beam path, imaging beam path, conjugated planes and identification of the lenses which are subject to change when another mode is activated.

The electron optical system is based on constant spectrometer and objective lens conditions. Illumination and imaging system operate with constant planes. The optics are designed so that only one single lens or lens system is switched to another default value when another mode is activated, and only different imaging planes are changed for the respective focal planes. No auxiliary lenses exist. Irrespective of the illumination and imaging modes, all lenses are always in operation. This clearly reduces drift and provides extremely stable alignment.

When changing from image to diffraction (SAED), the first projector system is modified to the effect that the (rear) back objective focal plane instead of the first intermediate image plane is imaged in the spectrometer entrance crossover. Lens variations in the first projective system are also used to set the magnification.

When changing from diffraction (SAED) to convergent diffraction (CBED), only the third condenser lens is switched over. In doing so, the illumination system is converted from wide-field illumination of the sample plane to focussed point illumination automatically with an exactly defined probe diameter.

The spectrum mode can be set in every imaging mode, with only the first lens of the second projector system being focussed from the initial image plane of the spectrometer to the energy dispersive plane. The conjugated planes above the spectrometer then correspond to the respective beam paths.

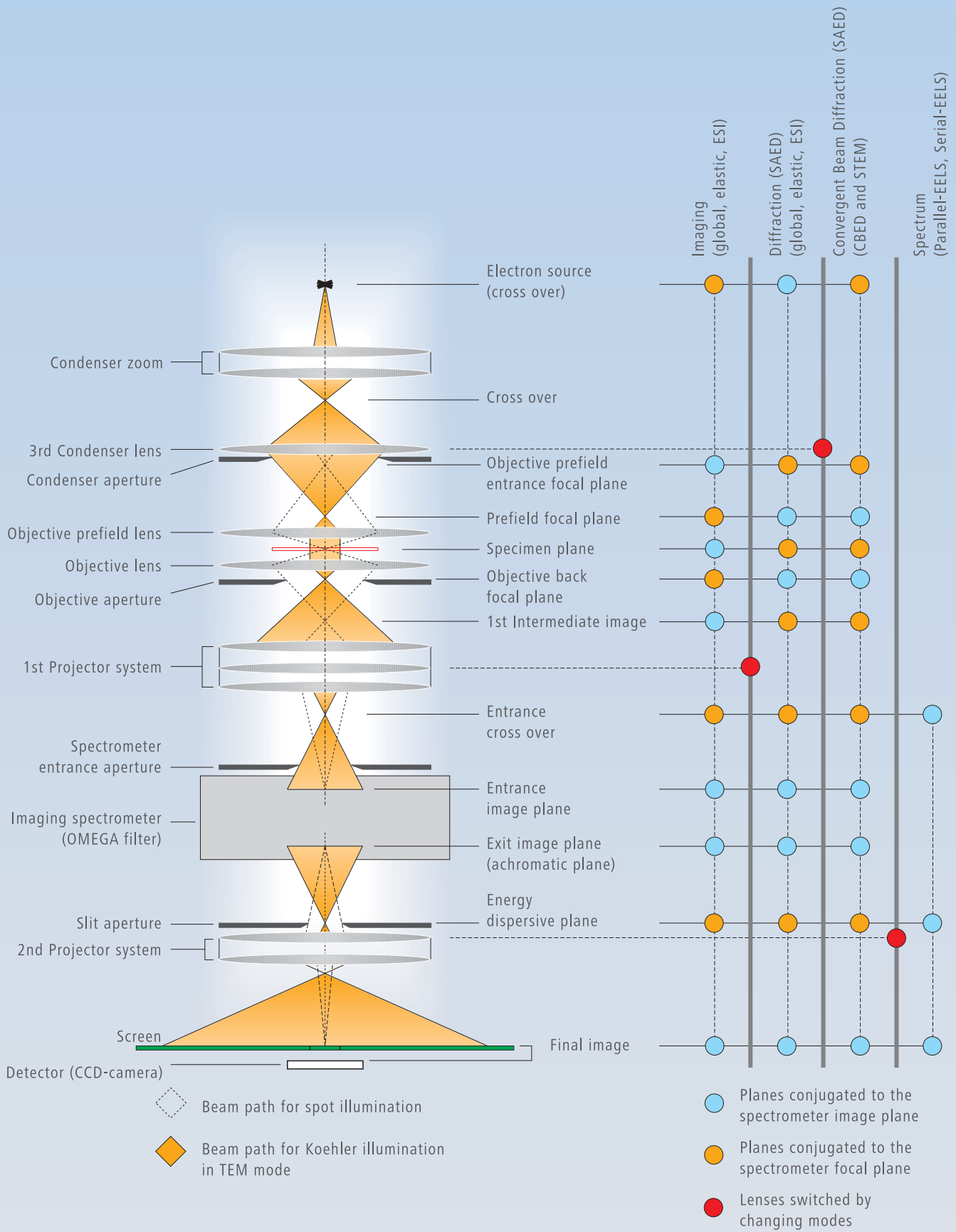


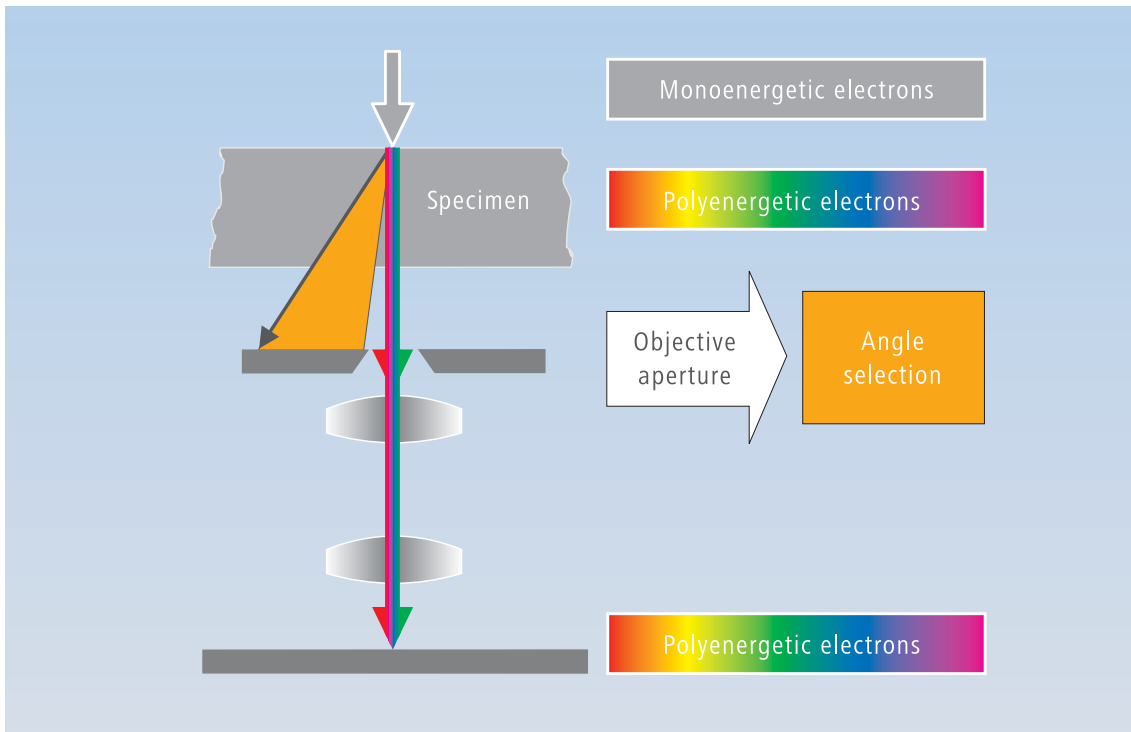
Image contrast and EFTEM characteristics

CTEM

contrast generation method

Image contrast is the decisive criterion for many applications, particularly when imaging light element specimens such as biological sections or polymers. Preparational techniques like chemical staining, for example, are used to create adequate contrast. In addition, physical methods exist, like the use of small lens aperture diaphragms, lenses with long focal lengths, or lens defocussing in phase contrast. All these methods, however, are only compromises and have an adverse effect on the image caused by artificial substructures and a deterioration of resolution.

In EFTEM, the contrast is optimised by an advanced technique, e.g. by filtering out the contrast reducing electrons from the spectrum of transmitted electrons, or by only allowing electrons containing specific information to be used for imaging. This method has no negative effects on resolution. Even unstained, thin specimens, frozen hydrated specimens or unconventionally thick specimens can be imaged with superb contrast in the physically exact focus, i.e. the Gaussian focus.



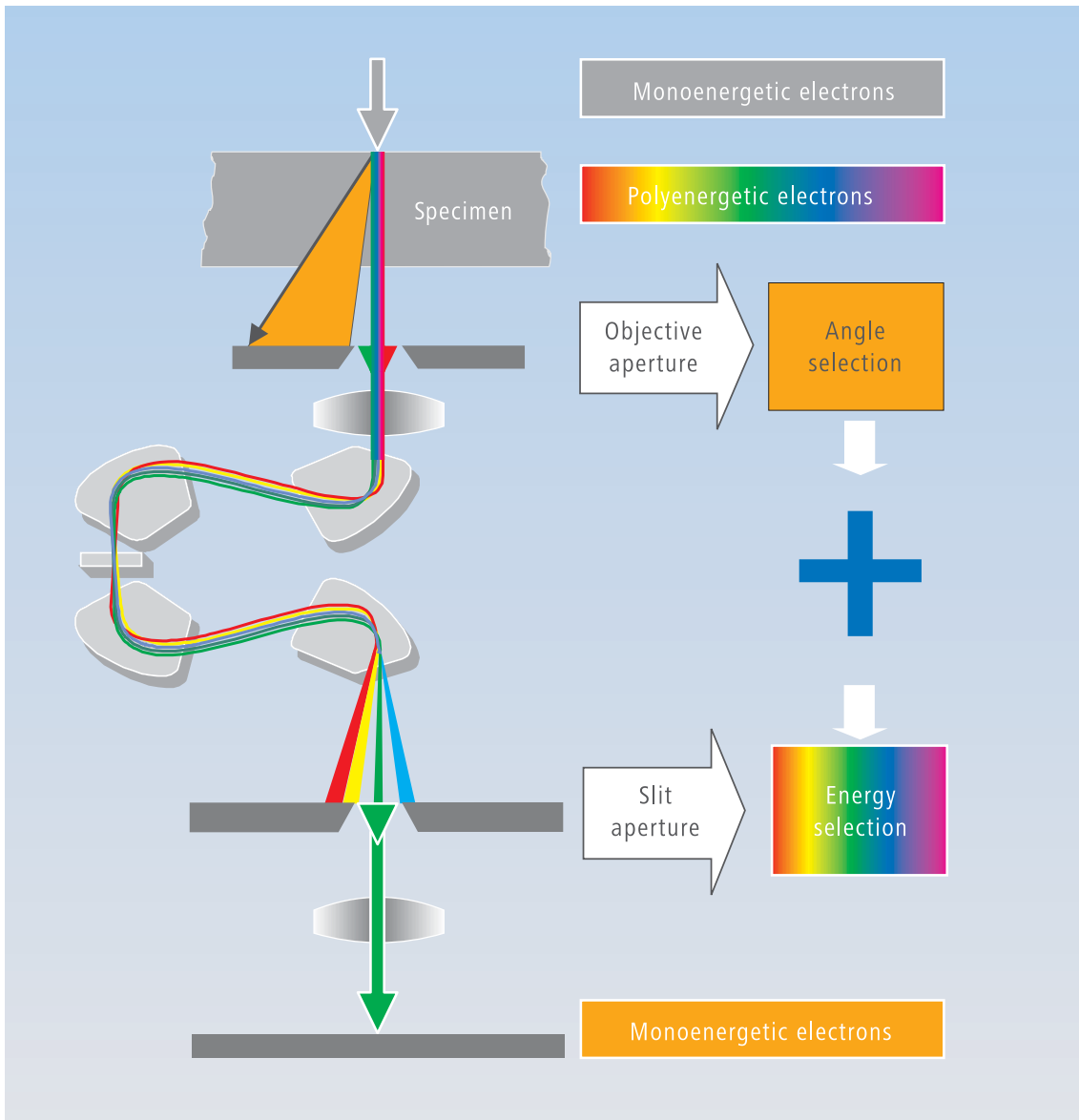
The specimen is exposed to monoenergetic electron radiation. As a result of the scattering in the specimen, a polyenergetic electron beam is produced.

In CTEM, electrons are selected from the electron beam via the lens aperture diaphragm according to their scatter angles. This angular selection results in scatter or diffraction contrast.

The image is formed by all electrons passing the lens aperture diaphragm, in other words with a polyenergetic electron beam.

Optics for contrast enhancement

EFTEM contrast generation method



In EFTEM, the transmitted electrons are subjected to an additional energy selection after the angle selection.

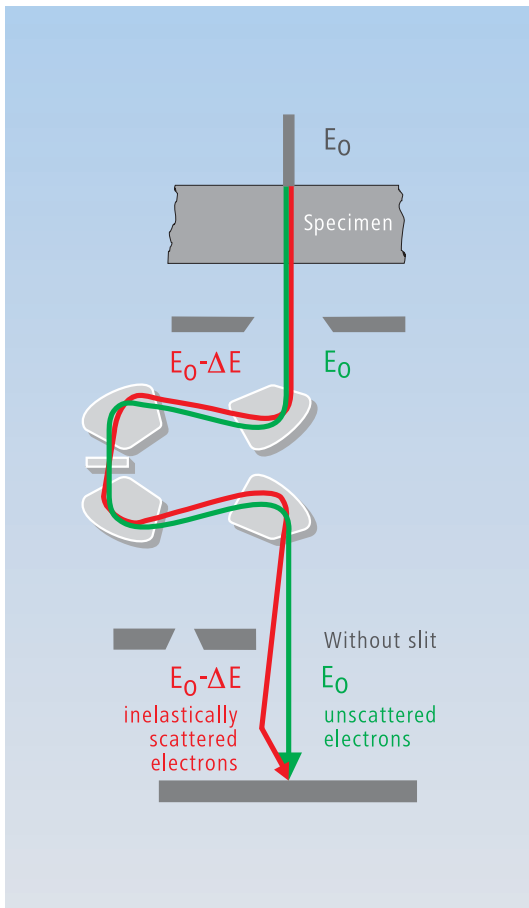
In the OMEGA filter the electrons are separated according to their energy (wavelength). The OMEGA filter acts as a spectrometer. The slit is used to select energy and energy bandwidth.

This additional electron selection results in contrast enhancement for all imaging modes and also provides the possibility of selecting electrons with specific scattering effects for imaging, thereby generating object or element specific contrasts.

Contrary to the CTEM method, the image is formed exclusively by a "monoenergetic" electron beam*.

*An electron beam with unscattered electrons also has a narrow energy bandwidth, which is defined by the nature of the cathode.

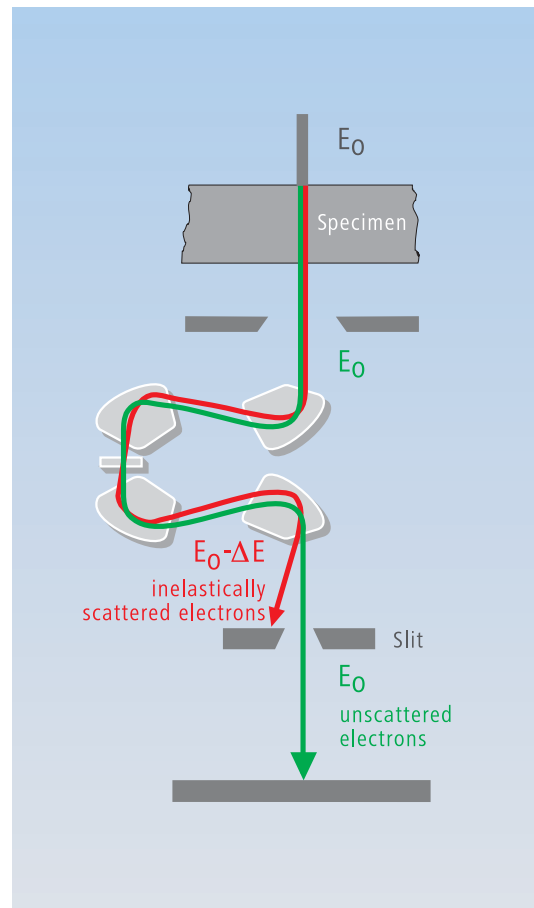
Principles of the new EFTEM imaging modes



Global imaging

The filter breaks down the electrons according to their energy (green with, red without energy loss), but the slit is not in the beam path. The second projector system combines all electrons into joint imaging.

The results correspond to the quality of CTEM images, where the advantages of the filter are not utilised.

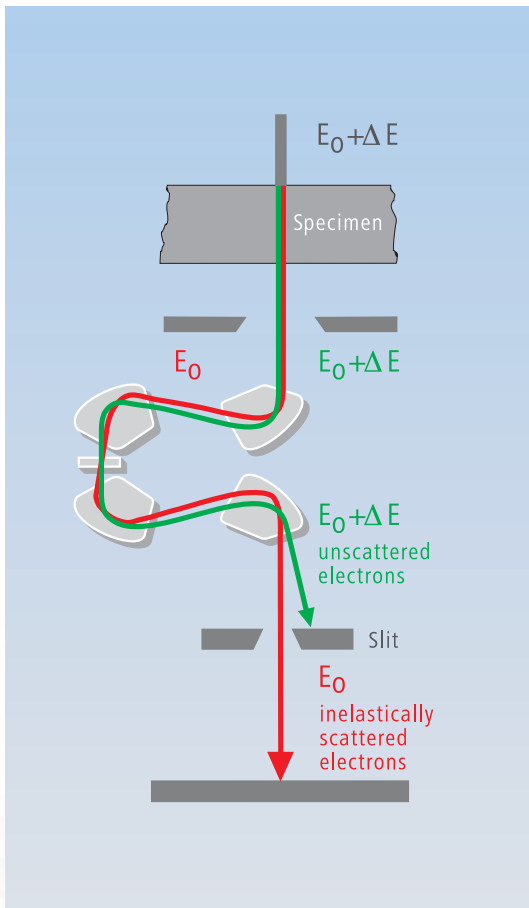


Elastic imaging

The slit is in the beam path. High voltage is set to the selected voltage, e.g. 200 kV. The slit allows only electrons without energy loss to pass. All electrons which have lost energy due to inelastic scattering are filtered out.

This mode enhances the contrast for all imaging modes such as bright-field, dark-field and diffraction.

Principles of the new EFTEM imaging modes



Inelastic imaging (ESI)

The slit is in the beam path. High voltage is increased by the required energy ΔE .

The slit position and the filter current remain constant. The slit only allows electrons to pass that have lost the ΔE energy and are therefore back to the rated voltage.

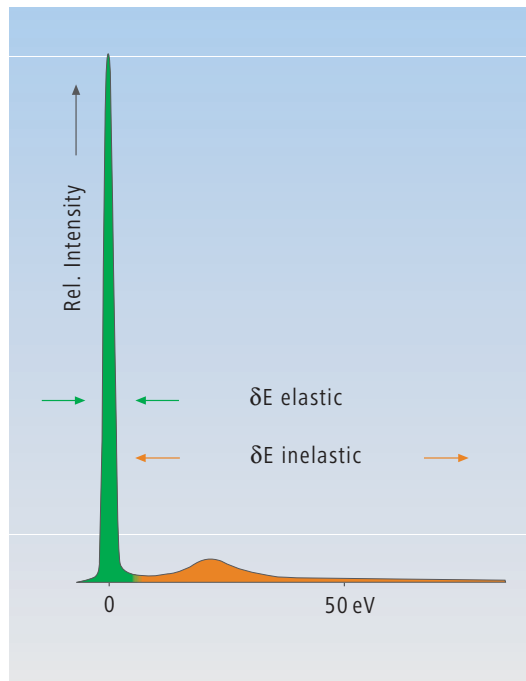
This mode is used for imaging with selective contrast on thin and thick specimens.

Special features of In-column EFTEMs with OMEGA filter

- In-column EFTEMs are as simple to operate as CTEMs.
- The patented layout of the filter between the first and the second projector system guarantees that the electron optical system retains all its conventional properties.
- The symmetrical design of the spectrometer compensates automatically for image errors, such as distortion in the achromatic image plane.
- The new, additional modes of operation of the OMEGA filter and its properties significantly enhance the application and performance range.
- In-column EFTEMs offer unrestricted flexibility for analog and digital image documentation in all imaging modes.

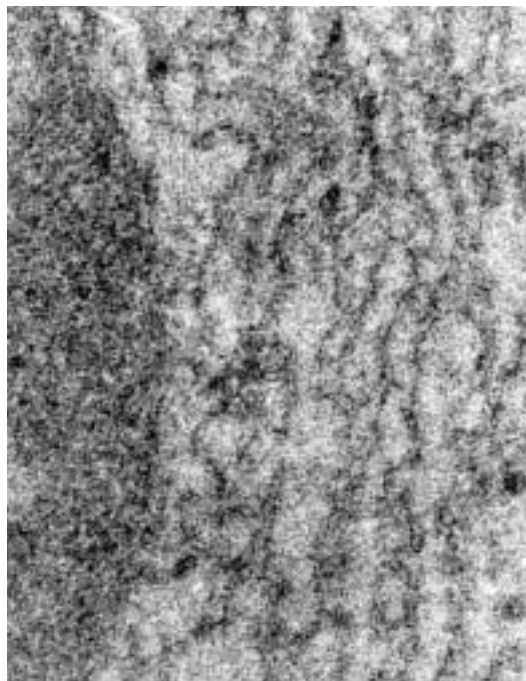
Principle of energy filtered imaging with unscattered and inelastically scattered electrons

The energy loss spectrum shows the scattering in thin specimens and the differences in energy bandwidths δE and intensities of unscattered and inelastically scattered electrons. The images below and to the right show an identical specimen location taken in the three imaging modes provided by EFTEM. They display the different contrasts that can be obtained with unscattered and inelastically scattered electrons and without any filtering of electrons.



Electron energy loss spectrum of the specimen shown below and to the right.

Specimen:
Cell core with endo-plasmatic reticulum. Conventional fixation and staining. Specimen thickness approx. 50 nm.



Unfiltered image of the same specimen location.

Global imaging:
As with CTEM imaging, the unfiltered image contains all inelastically scattered electrons with full energy bandwidth, which cause noticeable contrast deterioration.

Advantages of energy filtered imaging

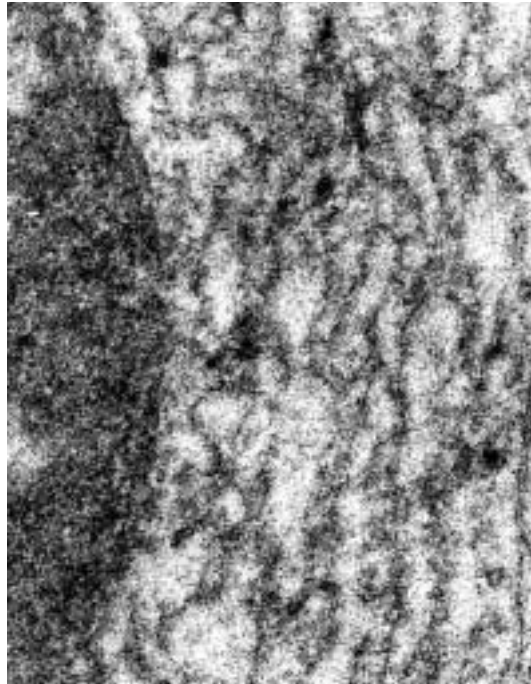
- Utmost contrast and highest resolution for thin, conventional and thick specimens.
- New information gained by structure or element specific contrast.
- Optimum resolution while imaging thick specimens with maximum depth of focus for stereo images.
- Balanced contrast and even definition in specimens of changing thickness.

Elastic imaging:

In the elastic bright-field image, the image contrast is produced by the electrons which were filtered out. Structures with higher mass filter out more electrons.

Therefore these structures are darker than their environment.

Despite the low specimen thickness and the number of elastically scattered electrons, the elastically filtered image clearly displays higher contrast than the unfiltered one.



Elastically filtered image of a thin, biological, conventionally prepared section.

Inelastic imaging:

For this, all inelastically scattered electrons marked orange in the energy loss spectrum were selected. It therefore shows imaging using the electrons which are filtered out in elastic imaging, and which cause the contrast deterioration in unfiltered imaging.

It also highlights the lack of definition caused by the chromatic aberration of the objective lens when electrons of high energy bandwidth are used for imaging.

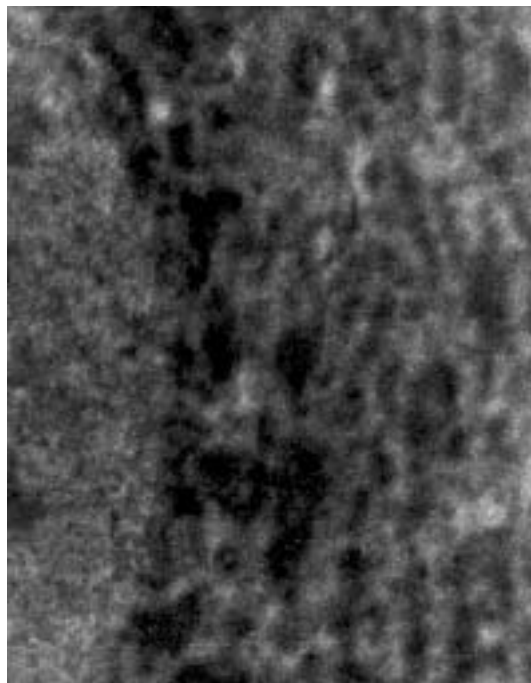


Image with inelastically scattered electrons of high energy bandwidth.

Elastic imaging

With elastic imaging, only monoenergetic, elastically scattered electrons from the wide spectrum of scattered electrons are used for imaging.

Contrast reducing, inelastically scattered electrons producing inverted contrast of the specimen structures, are filtered out. For this reason, even the contrast of thin and well contrasting specimens is further enhanced by filtered imaging.

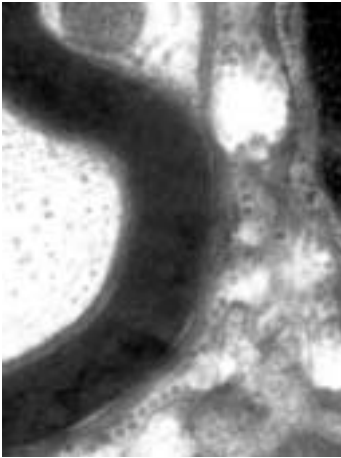
In the imaging of monoenergetic electrons, or electrons with narrow energy bandwidth, the chromatic aberration of the objective lens is less effective. Therefore, it is possible to image thick specimens without any loss in contrast or resolution.

Inelastic imaging

Inelastically scattered electrons generate a dark-field image of thin specimens. The specimen thickness, the mass of the specimen structure and the element specific scattering cross section influence the contrast.

For inelastic imaging, specifically scattered electrons with narrow energy bandwidth are selected from the wide electron spectrum. This creates a contrast which is either structure sensitive, phase sensitive or element sensitive.

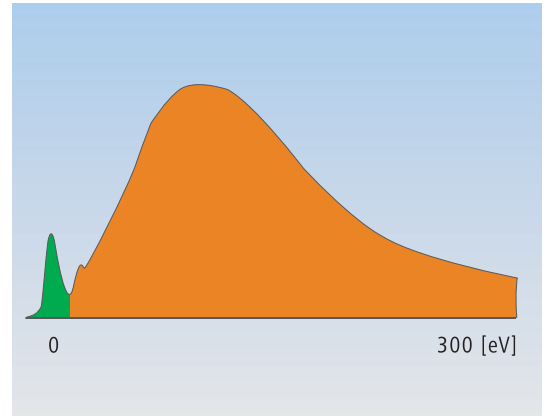
Improved resolution and enhanced contrast filtered imaging of thick specimens



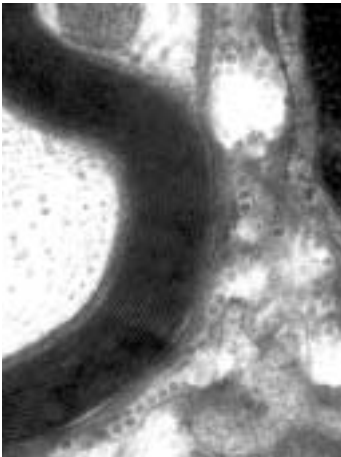
Nerve section of about 500 nm in thickness.

Global (like CTEM) imaging with polyenergetic electrons.

In CTEM imaging, imaging is always performed with the complete bandwidth of scattered electrons, whereby the chromatic aberration of the objective lens comes fully into play. CTEM images of thick specimens are therefore always blurred. The feasible specimen thickness is limited by the image quality needed.

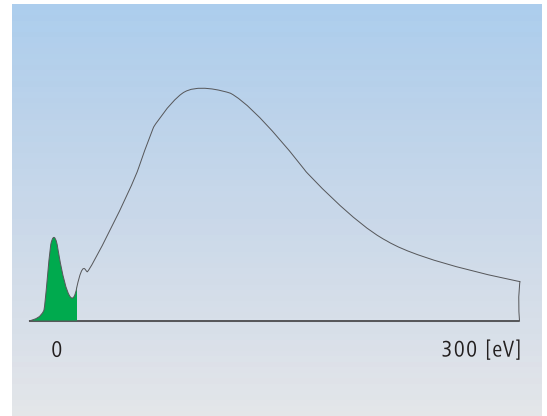


Full electron bandwidth in CTEM imaging.

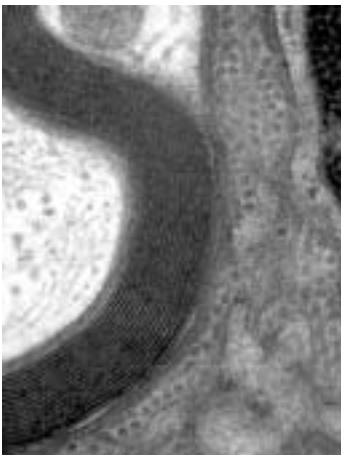


Elastic imaging with electrons without energy loss.

The selected, inelastically scattered electrons produce sharply defined, high contrast images. As filtering results in the imaging of fewer electrons, the necessary image brightness is a limiting factor of the possible specimen thickness.

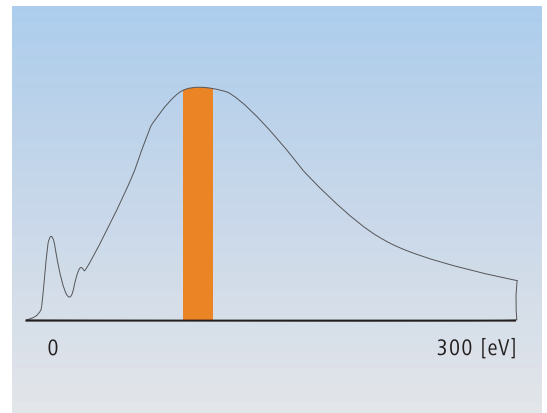


Electron selection (green) for elastic imaging.



Inelastic imaging with selected energy loss electrons of low energy bandwidth.

If energy loss electrons in the high intensity range are selected for imaging, the image brightness is increased. In this imaging mode, the specimen may be even thicker than with elastic imaging. Mass thickness effects, as they occur when cutting collagen, are eliminated here.



Electron selection (orange) for "contrast tuning".

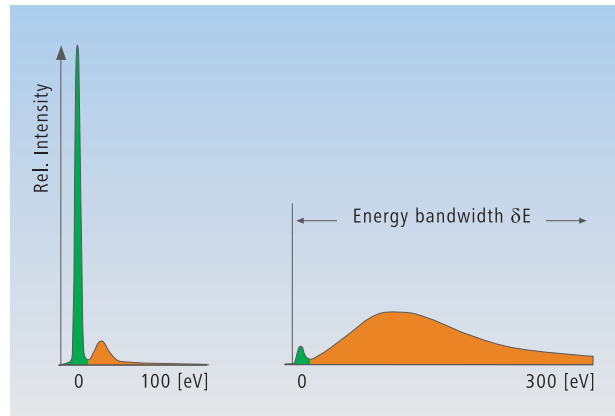
Contrast through

Energy filtering is particularly effective when imaging thick specimens, because the scattering conditions are different to those in thin specimens and many more electrons can be filtered out.

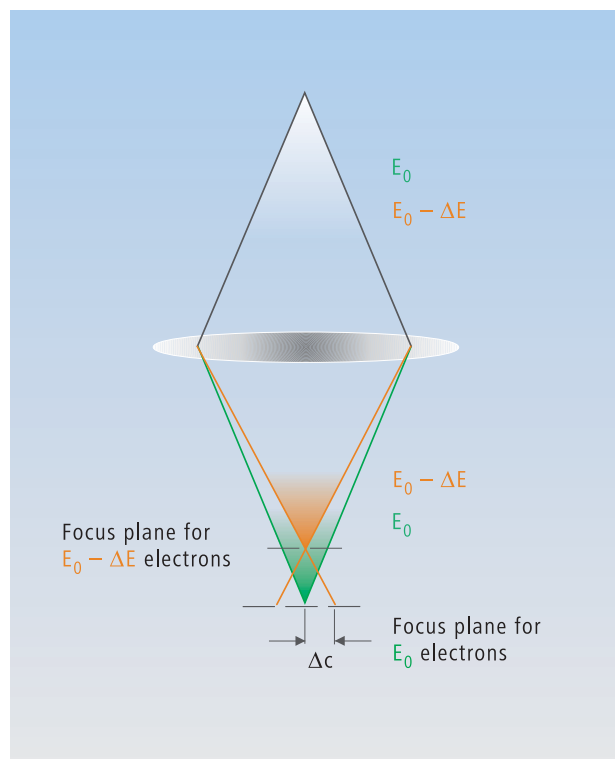
With thick specimens, the intensity of the zero-loss electrons is very low, as can be seen from the energy loss spectrum. Instead, a wide spectrum of polyenergetic electrons is present. As a result of the chromatic aberration of objective lenses, a sharply defined image can only be obtained with monoenergetic electrons. The full effect of the chromatic aberration is seen when using polyenergetic electrons with a greater energy bandwidth for imaging, as in CTEM. Therefore CTEM images of thick specimens are always blurred, even when they are taken with a high acceleration voltage.

Filtered imaging with low energy bandwidth, on the other hand, produces sharply defined, high resolution images, which in CTEM can only be obtained from thin specimens.

Energy loss electrons are also suitable for filtered imaging. The contrast can even be varied by choosing different energy loss settings. This is possible because the scattering is a function of mass. Mass thickness effects, such as those created by cutting artefacts, can be reduced or eliminated by “contrast tuning”. This considerably enhances the information content of the image.



Electron energy loss spectra of Epon sections of different thickness. Left: Section thickness 50 nm, right: 500 nm. Green: Monoenergetic electrons, orange: Polyenergetic electrons. In these specimens, monoenergetic, elastically scattered electrons prevail, whereas inelastically scattered electrons with large energy bandwidth dominate in thick specimens.



Schematic diagram of the chromatic aberration. Δc radius of chromatic aberration disk. The focus has only been corrected for electrons of one energy. Electrons of other energies miss the exact focal plane.

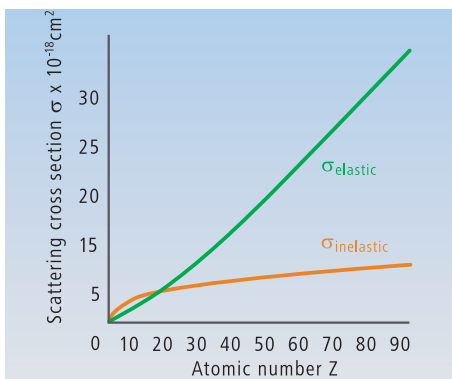
Near focus high contrast imaging of frozen hydrated specimens

Frozen hydrated specimens come very close to the natural state of a biological specimen, because they have not been tampered with in the form of chemical fixation or additional staining. Therefore, cryo transmission electron microscopy is steadily gaining momentum in life science research.

Biological specimens consist primarily of light elements. Without staining, they display very little scattering contrast. The high water content in frozen hydrated specimens additionally impairs the contrast, because in ice far more electrons are scattered inelastically than elastically. For this reason, adequate contrast is normally obtained by strongly defocussing the objective lens, making use of phase contrast. This makes artificial structures hard to interpret.

Elastic imaging considerably enhances contrast, as it permits not only the filtering of the few elastically scattered electrons, but also the more frequent inelastically scattered ones. Defocussing may therefore be considerably reduced.

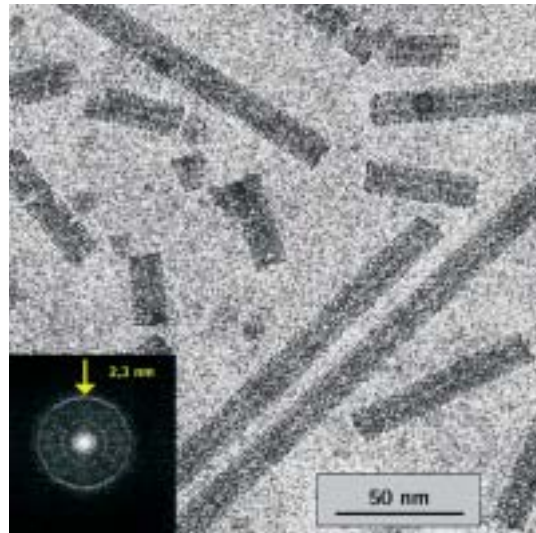
Energy filtering as such does not enhance resolution beyond the specification, but it prevents the deterioration in resolution caused by inelastically scattered electrons and defocussing artefacts.



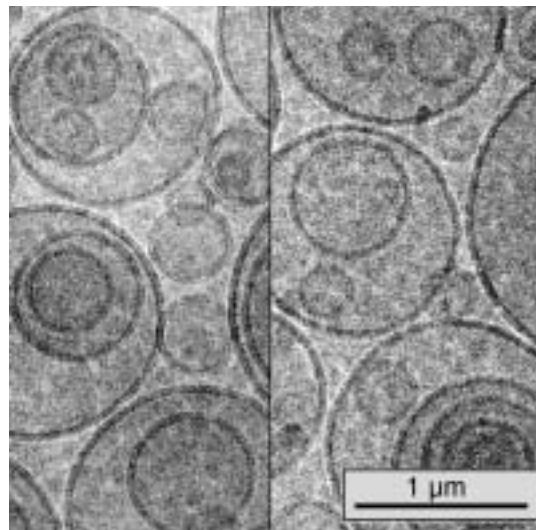
Elastic and inelastic scattering cross sections [σ] as a function of the atomic number Z: In biological specimens containing light elements, the number of elastic scattering events is very low. It increases with higher atomic numbers.

In elements with an atomic number below 10, it is considerably lower than even inelastic scattering. This is the main reason for the low contrast in the images of frozen hydrated specimens.

Langmore et al. (1973)



Elastically filtered image of frozen hydrated tobacco mosaic viruses (TMV). Fourier transformation (FFT) shows the periodicity of 2.3 nm of the TMV. Specimen temperature 100 K, acceleration voltage 100 kV, objective aperture 4 mrad, primary magnification 40,000x, defocus 3 μm , dose 800 e $^-$ /nm 2 . Detector: Slow Scan CCD-camera 1024x1024 pixel, 14 bit grey levels.



Frozen hydrated liposomes. Specimen temperature 100 K, acceleration voltage 120 kV, primary magnification 40,000x, defocus 800 nm, objective aperture 4 mrad, dose 1500 e $^-$ /nm 2 . Detector: Negative, format 3/4 x 4". Left: Elastically filtered image.

Right: Unfiltered image of another specimen location with exactly the same radiation exposure, the same specimen thickness, identical magnification and defocussing. The unfiltered image displays less contrast, lower resolution and visibly more background noise.

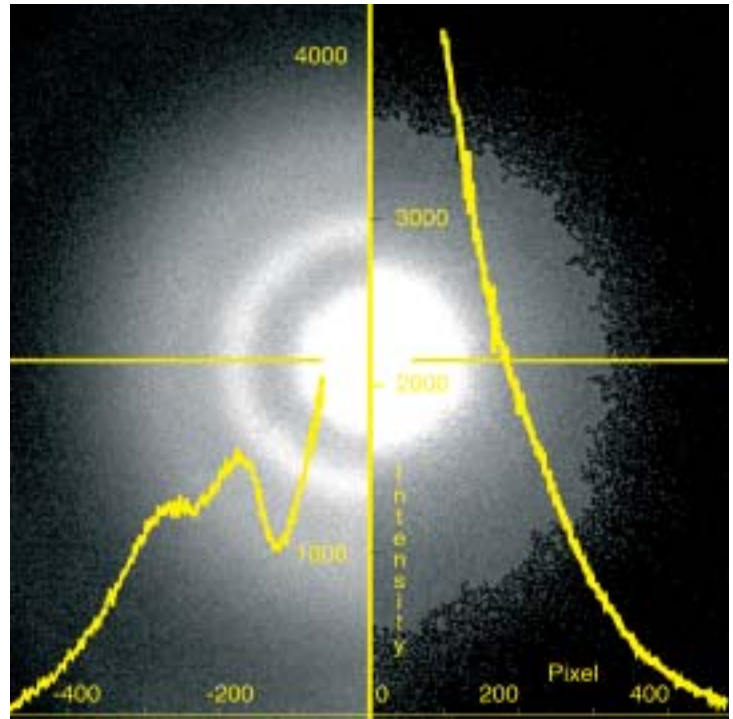
Appreciably higher information content through crisp, quantifiable diffraction images

In diffraction images, inelastic scattering causes blur and bright halos around the zero beam and each individual reflex. The filtering out of inelastically scattered electrons creates brilliant, distortion-free and quantifiable diffraction images.

The information content of filtered diffraction images is higher, because closely adjacent reflexes are separated when interfering halos are filtered out. Also, reflexes of large lattice distances are visible in the zero order area. Carl Zeiss SMT EFTEMs provide all diffraction methods, such as selected area electron diffraction (SAED), nanoprobe diffraction (Nanoprobe), low angle electron diffraction (LAED) and convergent beam diffraction (CBED).

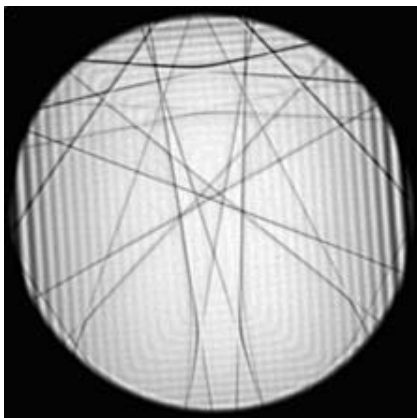
Filtering depends on thickness, also in diffraction. It is above all recommended in convergent diffraction where thicker specimens are observed, so that a 3D impression of the crystalline structure can be gained.

It is also possible to obtain diffraction diagrams with selected energy loss, e.g. for the analysis of channeling effects.



Comparison of diffraction images of a radiation sensitive, amorphous film of polysiloxans with uranium dioxide (2+)- complexes with intensity profile. Left image: Elastically filtered diffraction taken with Slow Scan CCD-camera. Right image: Unfiltered diffraction image of an adjacent specimen location. The filtering out of the inelastically scattered electrons causes a diffuse diffraction ring, which remains invisible in the much brighter, unfiltered image. By energy filtering of diffraction images, even weak reflexes with narrow scattering angles can be visualised.

Courtesy of Dr. Fang Zhou, University of Tübingen



Filtered convergent diffraction (left) and unfiltered image (right). Taken with Slow Scan CCD-camera.

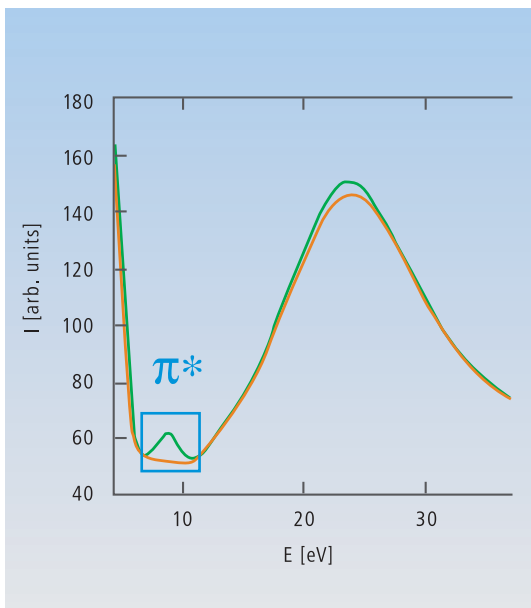
Specimen: Aluminium, $T=220$, orientation to $[2\ 3\ 3]$ zone axis.

Courtesy of Prof. J. Mayer, MPI Stuttgart, now at RWTH Aachen

New specimen information through structure and element sensitive contrast

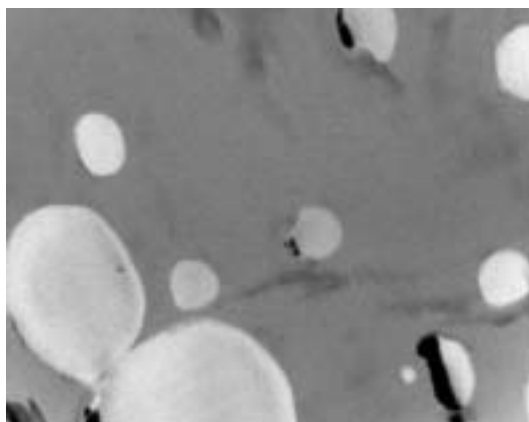
In inelastic scattering, specific as well as non specific scattering occurs. This may be structure, phase or element specific. If specific scattering effects are selected for imaging, previously inaccessible specimen information can be obtained.

Structure specific contrast is used for imaging thin, unstained specimens, phase contrast for aromatic combinations in polymer specimens, for example, and element specific contrast for element distribution images.

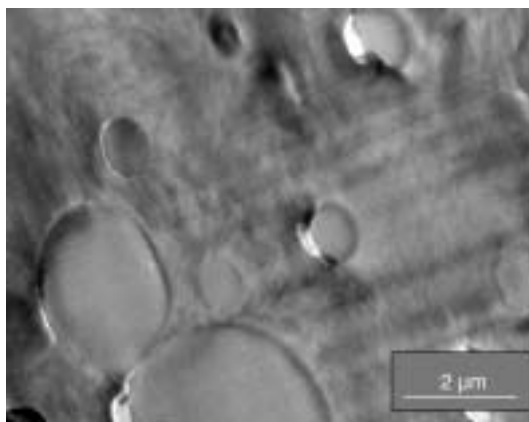


Energy loss spectra of a polymer sample.
Green spectrum: Polyphenolenether (PPE) particles.
Orange spectrum: Polyamid (PA) matrix.

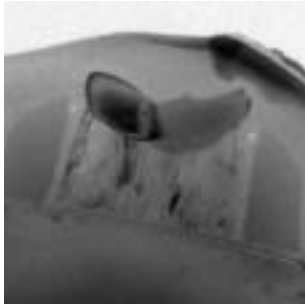
The PPE particles produce a marked energy loss peak at 6.4 eV with a narrow bandwidth. The energy range marked with a frame was selected for phase specific imaging below.



Phase specific imaging of PPE particles with selected carbon π^* plasmon electrons.
Specimen: PA+PPE polymer sample, unstained.
Instrument parameters: HV 120 kV, ΔE 6.4 eV, δE 2 eV.
Objective aperture 12 mrad, dose 750 el./mm², magnification 1500x,
detector: VarioSpeed™ SSCCD-camera.

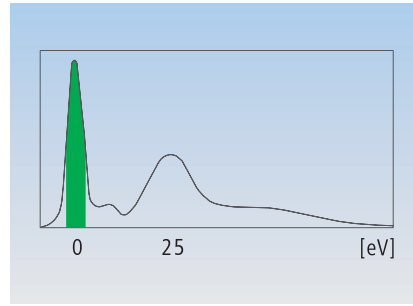


Elastic bright-field image of the same specimen location as above.

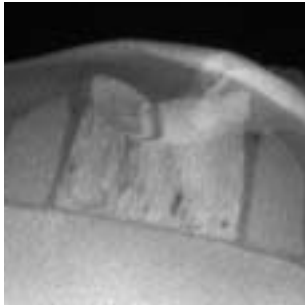


Elastic imaging of an ion-thinned semiconductor sample (DRAM).

Digital image with VarioSpeed™ CCD-camera, exposure time 1 s each.

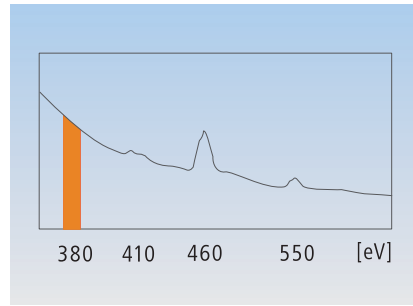


Partial spectrum with energy range (green) for elastic imaging.

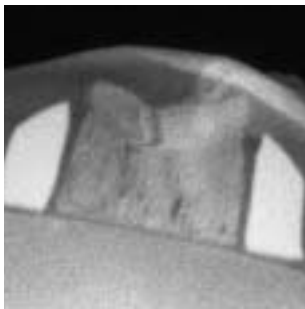


Inelastic imaging with energy loss electrons of 380 eV. The selection lies in the energy loss spectrum below the nitrogen absorption edge.

Due to the increase of inelastic scattering with higher mass thickness, thicker sample areas are brighter than thinner areas.

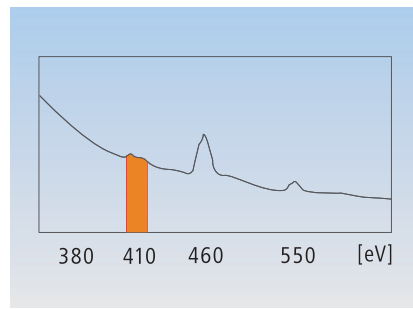


Partial spectrum with energy range (orange) for inelastic imaging.

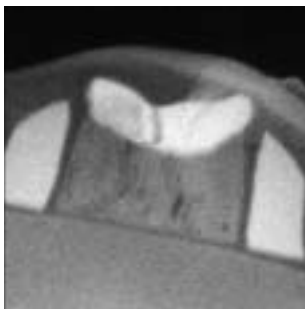


Nitrogen-sensitive image with 410 eV energy loss electrons.

Due to the increase in energy at the nitrogen absorption edge, sample areas containing nitrogen are brighter than the same area in the 380 eV image.

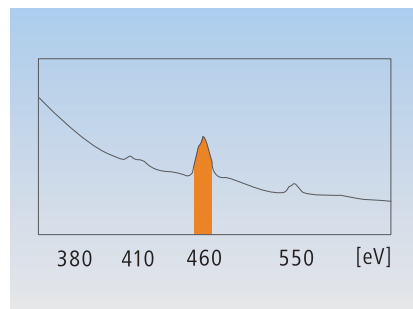


Partial spectrum with energy range for nitrogen-sensitive imaging.

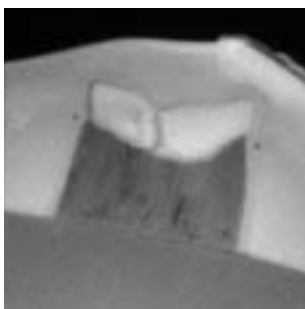


Titanium-sensitive image with 460 eV energy loss electrons.

Due to the increase in energy at the titanium absorption edge, sample areas containing titanium are brighter than the same area in the nitrogen-sensitive image.

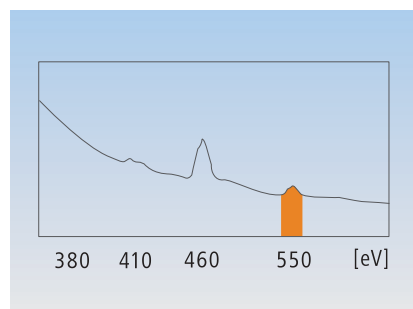


Partial spectrum with energy range for titanium-sensitive imaging.



Oxygen sensitive image with 550 eV energy loss electrons.

Sample areas containing oxygen are brighter than the same area in the titanium-sensitive image.



Partial spectrum with energy range for oxygen-sensitive imaging.

Highly resolved element distribution images simply and rapidly with EFTEM

Three-window method for the creation of element distribution images

An element distribution image shows the relation of the chemical compound to the structure. In conventional EDX mapping the local resolution is limited.

In addition, the time required for recording an image of high information content is very long, because serial procedures are very time consuming.

With EFTEM, element distribution images are taken in parallel and therefore very quickly and with high local resolution.

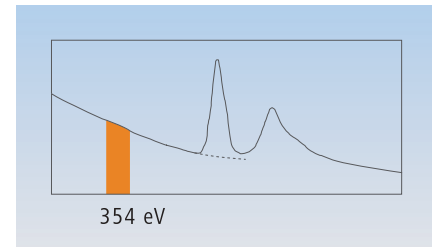
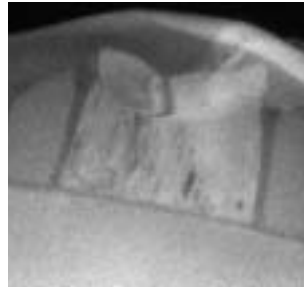


Image at 354 eV

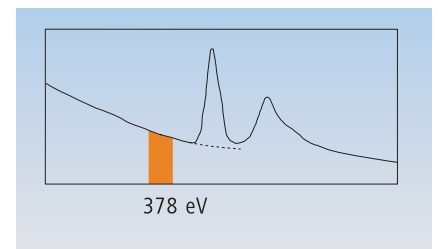


Image at 378 eV

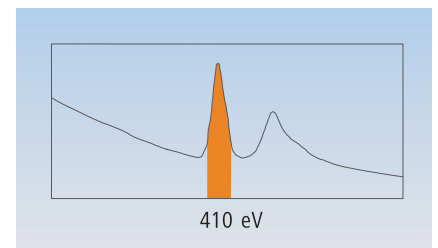
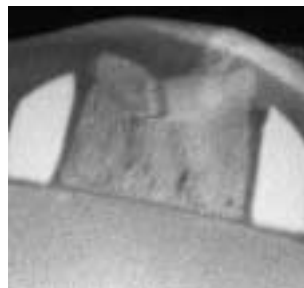
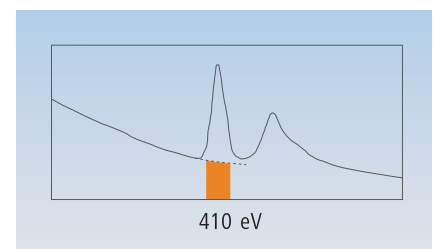
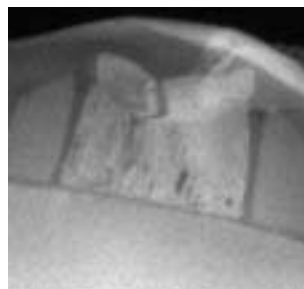


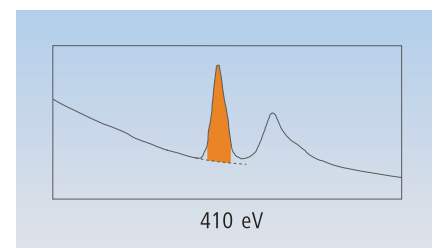
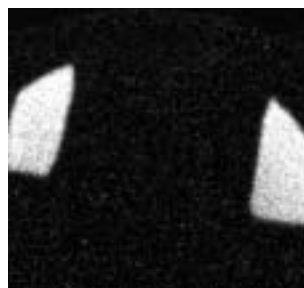
Image at 410 eV

An element distribution image is generated in several steps.

First, an image in the vicinity of the element absorption edge is taken (410 eV) which contains element specific information, then two images below the absorption edge (378 eV and 354 eV) which define the background. Following this, a background image is computed pixel by pixel by extrapolation, which corresponds to the background below the absorption edge. At the same time, this image is subtracted from the element specific image. The result is an image which displays nothing but structures formed by the selected element.



Computed background

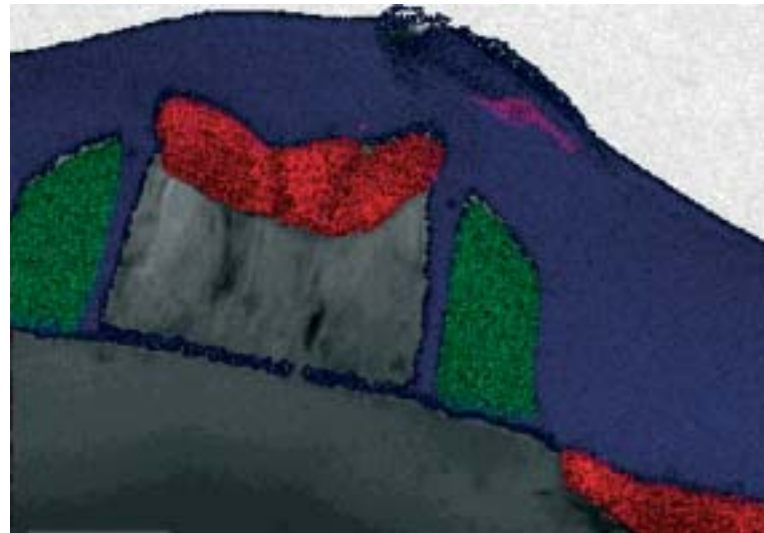


Element distribution (N)

Images obtained

Element specific images contain not only specific information, but also background information. They are therefore not taken directly, but in several stages. First, an element specific image is taken, then background images below the absorption edge, and from these one background image is calculated. As a next step, the background is subtracted from the element specific image so that an element distribution image is obtained. Several algorithms are available for background computation, e.g. the two-window, three-window and white-line methods.

Image recording and processing is performed using image analysis systems with special software for EFTEM applications. The EFTEM image recording process is automatically controlled and the subsequent image computation is fully automated. This enables, with great speed and ease, high resolution element distribution images of high information content.



Elastic bright-field image of a semiconductor sample, superimposed by three high resolution element distribution images.

Red: Ti distribution

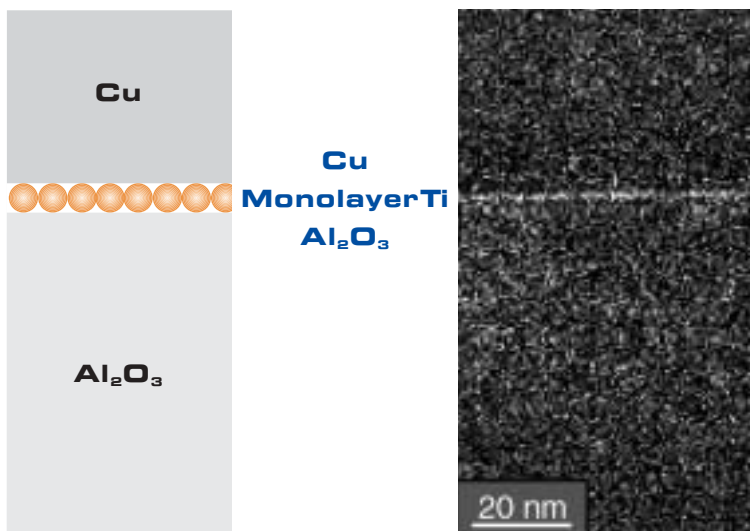
Green: N distribution

Blue: O distribution

Detector: Slow Scan CCD-camera

Exposure time per frame 1s.

Background computed by three-window method.



Ti distribution image of a monolayer of titanium atoms on a Cu-Al₂O₃ interface.

Left: The model.

Right: The element distribution image indicates the high detection sensitivity and lateral resolution of the ESI method.

Courtesy of Prof. J. Mayer, MPI Stuttgart, now at RWTH Aachen

Comprehensive element analysis using EELS, ELNES, EXELFS and EDX

EFTEMs are ideal instruments for analytical applications and combine high versatility with extreme ease of operation. The patented electron optics incorporate an objective lens which has been optimised for analytical applications. All known detection systems for imaging and analysis can be mounted without any performance deterioration. The Koehler illumination also facilitates operation. X-ray microanalysis (EDX) in conjunction with the STEM attachment supplies excellent results both from a qualitative and a quantitative viewpoint when analysing thick specimens.

Electron energy loss spectroscopy (EELS) offers more advantages for the analysis of thin specimens. EELS provides higher spatial resolution, higher detection sensitivity and higher energy resolution than EDX. In addition to atom analysis EELS permits the analysis and imaging of chemical bonds, because differences in the fine structure can be analysed at the absorption edges due to the high energy resolution. ELNES* is used to analyse fine structures close to the absorption edge and EXELFS** away from the absorption edge. Fine structure is produced through the influence of adjacent atoms and provides information on chemical bonds.

The three following methods, which can be used simultaneously on the instrument without restriction, are available for production of energy loss spectra.

* ELNES: Energy loss near edge structure

** EXELFS: Extended energy loss fine structure

Image EELS

This method is particularly suitable for analysing minimum element concentrations on specimen structures of any shape, and for imaging chemical bonds. Spectra from defined specimen areas can be gained from a stack of images taken with different image losses. The analysis is performed in the image memory of an analyser system with special EFTEM software. In addition, element distribution images can be produced from the stack of images.

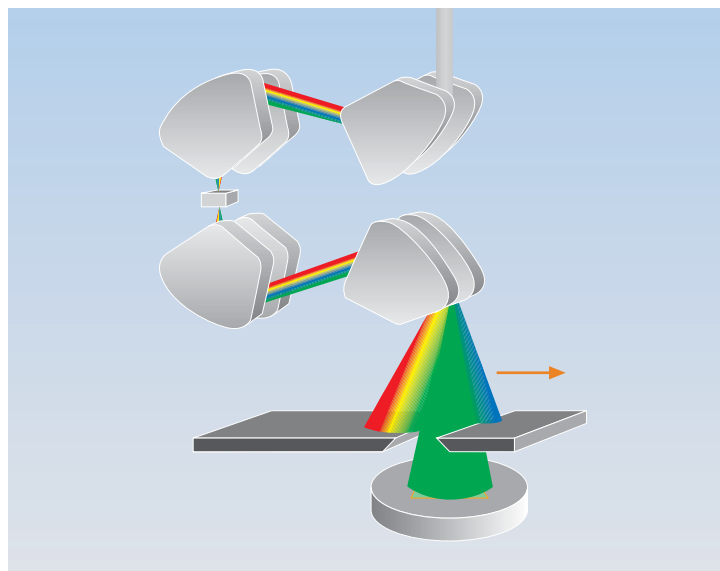
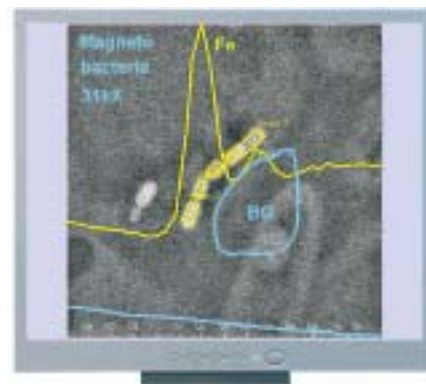


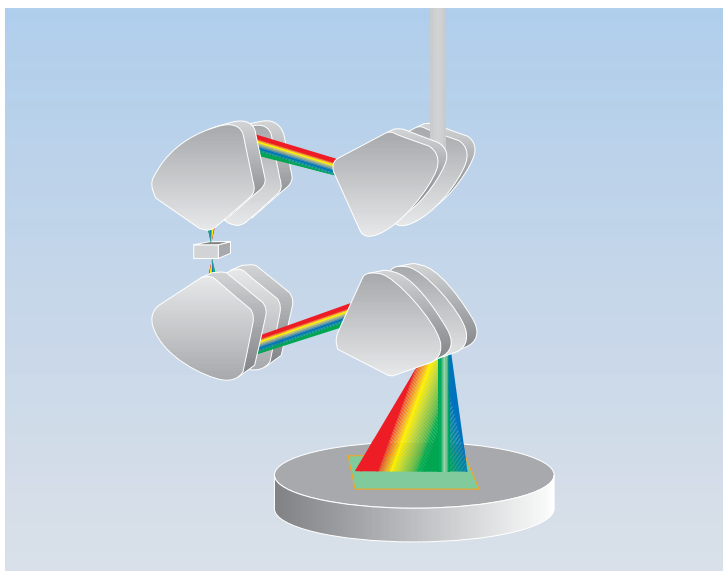
Image EELS: First, a series of images is taken at different energy losses, these are stacked in the image analysis system and the structures to be analysed are marked. The markings are automatically transferred to all images of the stack. The image analysis system measures the intensity of each mark and enters it in the energy loss diagram of each image. Energy loss spectra of all marked areas are obtained simultaneously. Images can be selected from the stack on the basis of the spectra, which allows the generation of element distribution images and distribution images of chemical bonds (chemical bond mapping).



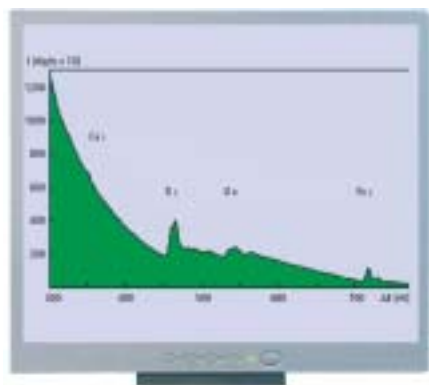
EFTEMs:

Parallel EELS

Parallel EELS is a technique for the rapid analysis of radiation sensitive specimens. The spectrum can be determined simultaneously in several ranges of 100 eV, with the electron spectrum being imaged using a high resolution CCD-camera. An image analysis system measures the intensity and converts it into an energy loss spectrum.

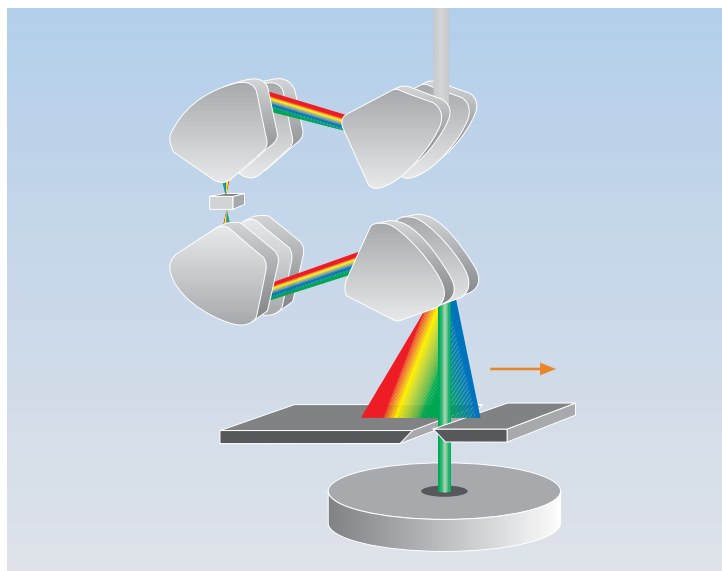


Parallel EELS: The specimen area to be analysed is selected by means of a diaphragm or a defined illumination spot. In the spectrum mode, the spectrum is then imaged on a Slow Scan CCD-camera, with the recording, illustration and evaluation being performed by an image analysis system with special EFTEM software.

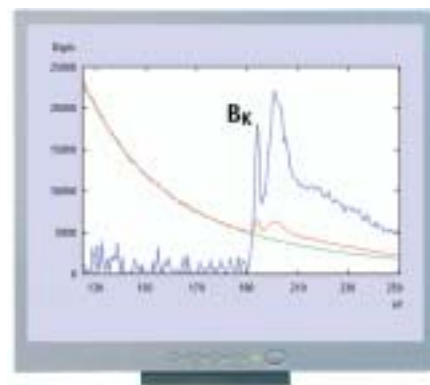


Serial EELS

Serial EELS permits the spectrum to be taken in a range of 0 eV to 2500 eV and with maximum signal digitisation of 18 bit. This is of special advantage for the evaluation of fine structures using ELNES and EXELFS. For recording, the electron spectrum is shifted over the detector by changing the high voltage in very small steps. A photomultiplier measures the intensity in the electron spectrum.



Serial EELS: The area to be analysed is selected in the same way as for parallel EELS, but the spectral intensity is determined sequentially by an electron detector and illustrated and evaluated in the image analysis system with special EFTEM software.



Boundless flexibility in analog and digital signal and image detection

Detector strategy for imaging and analysis

The interaction between the electron beam and the specimen produces signals which can be imaged and analysed. They contain a host of information about the specimen. Due to the additional energy dispersion, EFTEM permits more signals to be utilised than CTEM.

Carl Zeiss SMT has developed an integral design which incorporates all auxiliary units such as the digital scanning attachment, X-ray microanalysis and image analysis for example. Special care was taken to ensure that all the different detectors and cameras required for the detection of images and spectra can be mounted on the instrument at the same time without adversely affecting the specifications.

Documentation

Thanks to the spectrometer being an integral part of the electron optics, the entire spectrum of analog and digital documentation units for all imaging modes is available: Sheet film camera, STEM detectors, TV cameras and high resolution Slow Scan CCD-cameras.

Detectors in the objective lens area

The objective has very low constants of chromatic aberration and aperture error and still offers lots of room to move the different specimen holders, and also adequate space for an ideal detector configuration.

Specimen surfaces can be imaged with utmost resolution via the secondary electron detector and the backscattered electron detector (possible only with high-tilt objective lenses).

The EDX detector for X-ray microanalysis is designed for leading-edge detection sensitivity and minimum background noise. In conjunction with very small probe diameters, it is ideal for fast and precise specimen characterisation.

Detectors above the viewing window

A TV camera or high resolution Slow Scan CCD-camera can be attached to the wide angle port of the viewing chamber.

Detectors in the sheet film camera area

Conventional observation is made on the fluorescent screen. For the sheet film camera, films of different formats are available.

As an alternative, high resolution image plates for digital evaluation can be used which display an extremely high grey level.

Three detectors are located off-axis at the multi-detector housing: the STEM bright-field, the STEM dark-field and the electron detector for serial EELS.

The high resolution CCD-camera is located on the electron optical axis. It is suitable for recording any type of filtered or unfiltered images or, via parallel EELS, energy loss spectra.

Features

In-column OMEGA filter

- All conventional electron optical properties are retained due to the patented spectrometer configuration
- Symmetrical spectrometer design ensures automatic compensation of image aberrations, e.g. distortion in the achromatic image plane
- Optimum adaptation of achromatic field size and spectrum detail to detector size and user requirement due to a variable, second projector system

Digital electronics and WinTEM™ user interface

- New digital electronics with sub-ppm stability
- Very high reproducibility and speed when executing repeat functions
- High integration of electronics on only a few boards
- Minimum alignment effort due to extra high stability and the storage of user data

State-of-the-art vacuum technology

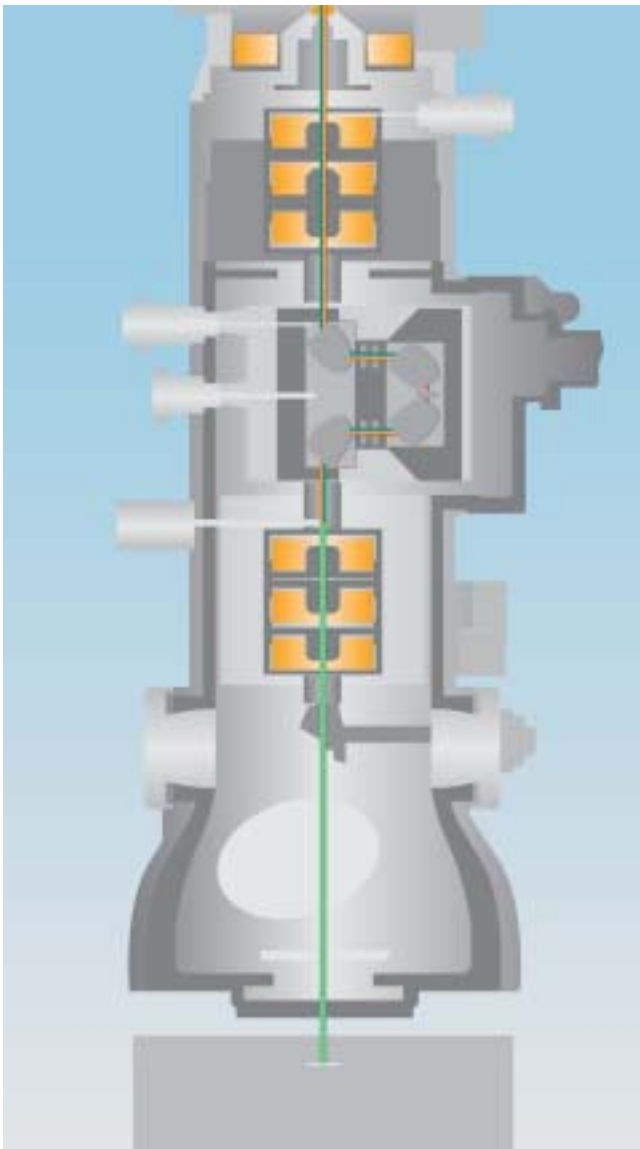
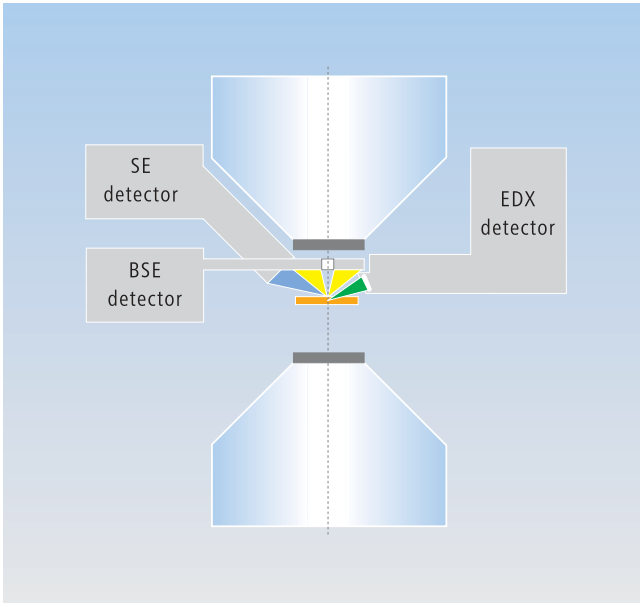
- Optimum specimen protection against hydro-carbon contamination
- Instant readiness for operation, fast specimen exchange times
- Minimum maintenance required

Computer controlled goniometer

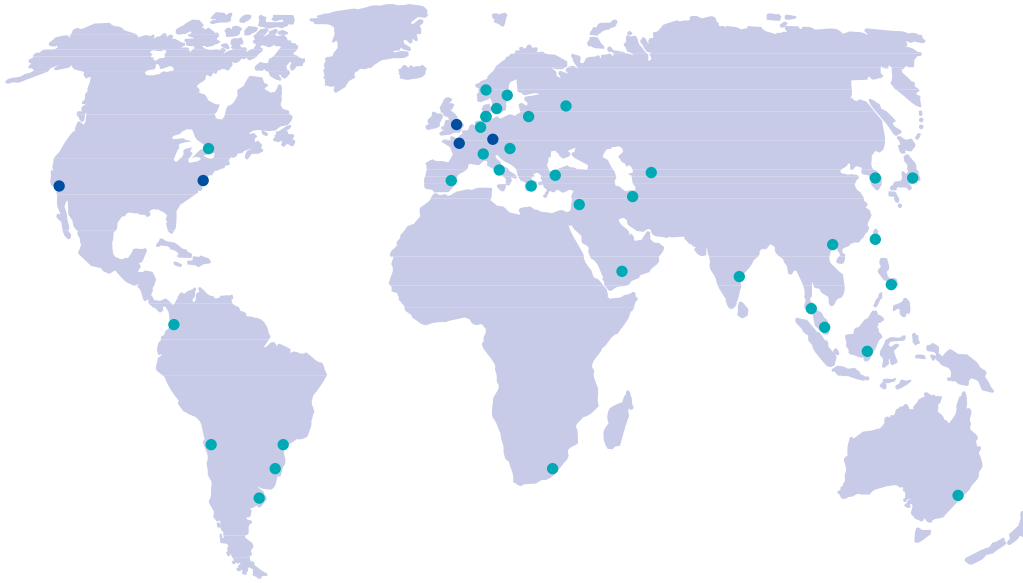
- High-precision specimen positioning in 4- or 5-axes
- Automatic return of stored specimen positions
- Up to 70° α -tilt possible in high-tilt (HT) pole piece geometry

Benefits

- Brilliant imaging of conventional specimens
- High contrast imaging of unstained, thin specimens
- New specimen information through structure and element sensitive contrast
- Maximum resolution, optimum depth of focus and individual contrast balance in the imaging of thick specimens
- Element imaging and comprehensive element analysis with ultimate detection sensitivity and maximum local resolution
- Minimum preparation work required
- Conventional operation, no additional alignment required
- Superb performance in imaging and analysis
- No performance deterioration when using attachments, due to integral instrument concept



Carl Zeiss SMT worldwide



- Carl Zeiss SMT
- Distributor

Global Solution Provider

The Nano Technology Systems Division of Carl Zeiss SMT provides its customers with total solutions featuring the latest leading-edge EM technology. The company's extensive know-how, meticulously acquired over 60 years in the field of E-beam technology, has brought many pioneering innovations to the market. Our global applications and service network guarantees fast, reliable and high quality support sharply focused on customer requirements. Combined with dedicated upgrade strategies, this will protect your investment for its entire lifetime. The core technology embedded in our innovative products enables us to provide solutions which add value to our customers' business.

Enabling the Nano-Age World®

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