Monochromator and spectrometer design for ultra-high energy resolution EELS

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Achieving 6 meV electron energy loss spectroscopy (EELS) resolution at 60 keV primary energy (Fig. 1) amounts to a resolution of 1 part in 10^7. This is 10x higher fractional resolution than when a typical aberration-corrected electron beam of 100 um diameter is focused into a 1 Å probe, and it is therefore a stricter test of instrumental performance than high resolution imaging.

Fig. 2 shows the electron trajectories through a monochromated scanning transmission electron microscope (STEM) capable of this kind of performance. The electron source is imaged into all the planes in which high resolution is needed: first as the energy-dispersed zero loss peak (ZLP) in the spectrum formed at the monochromator's energy-selecting slit, then as the non-dispersed, sub-Å electron probe formed at the sample, and finally as the ZLP in the EEL spectrum formed on the EELS detector. The successive images are closely related: if the ZLP formed at the slit shakes because a dipole in the monochromator is not sufficiently stable, the probe at the sample will shake too. This means that the stability requirements placed on the ZLP at the monochromator slit must be just as stringent as the requirements placed on the probe-forming optics. This can be achieved if the monochromator uses the stability-enhancing design principles we developed for our aberration corrector.

Our monochromator design therefore focuses on precise mechanical construction, uses multipoles with up to 12-poles to correct high-order aberrations, alignment dipoles whose strength is minimized by accurate mechanical alignment, and software that tunes its electron optics automatically. For optimum EELS energy resolution, our spectrometer employs the same design principles [1], and also uses 16-poles to create rotatable 12-poles so that all aberrations up to 5^{th} order can be fully corrected. The monochromator and the spectrometer use linkage schemes that make the EELS resolution insensitive to variations in the high tension and the prism current. Full attention is paid to shielding against external disturbances, with rigid mechanical construction and double to quadruple mu-metal shielding.

The monochromator, the probe-forming optics and the spectrometer are all ultimately limited by diffraction, and to achieve better resolution (smaller probe size or narrower ZLP), the angular range of the beam focused into the probe or the ZLP **must be increased.** For probe formation, this is well understood: high resolution STEM specialists appreciate that the probe corrector's task is to allow higher angles to contribute to the electron probe, thereby making the diffraction limit smaller and the attainable resolution better. At their highest energy resolution, the monochromator and the spectrometer now also operate in diffraction-limited regimes. This seems counterintuitive for EEL spectrometers, in which better energy resolution has traditionally been achieved with **smaller** entrance apertures. The fact that for better resolution meV-level EELS, the EELS aperture needs to be **made larger** shows how far ultra-high energy resolution EELS has recently progressed.

The design of the monochromator and the new spectrometer will be reviewed, and their experimental capabilities illustrated by practical examples.

[1] TC Lovejoy et al, Proceedings M&M2018.

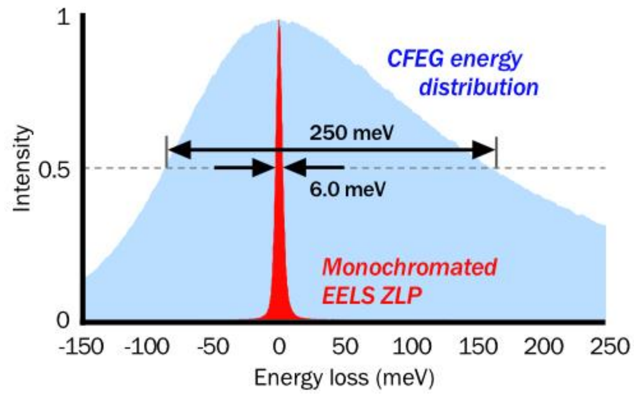

Fig. 1. Zero loss peak (ZLP) obtained at 60 keV primary energy with 100 ms acquisition time, ~11mrad half angle collection (β/2) compared to unmonochromated CFEG energy distribution.

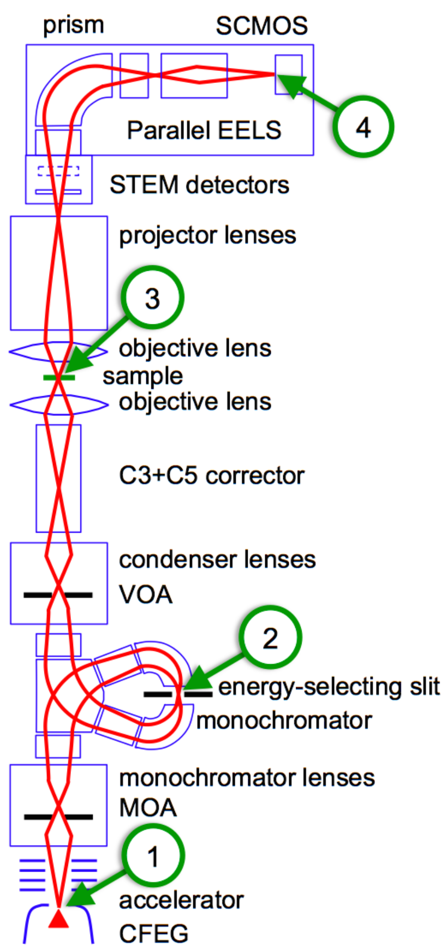

Fig. 2. Schematic diagram of the electron trajectories through the Nion ultra-high energy resolution monochromated EELS-STEM (U-HERMES). All the beam crossovers contain an image of the electron source; the most important crossovers are numbered: 1 = cold field emission gun (CFEG) virtual crossover; 2 = monochromator slit crossover; 3 = sample-level crossover; 4 = EEL spectrum crossover. (The trajectories are schematic and their widths are greatly exaggerated.)