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Experimental Setup for Energy-Filtered Scanning Confocal Electron Microscopy (EFSCEM) in a Double Aberration-Corrected Transmission Electron Microscope

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Abstract. Scanning confocal electron microscopy (SCEM) is a new imaging mode in electron microscopy. Spherical aberration corrected electron microscope instruments fitted with two aberration correctors can be used in this mode which provides improved depth resolution and selectivity compared to optical sectioning in a conventional scanning transmission geometry. In this article, we consider a confocal optical configuration for SCEM using inelastically scattered electrons. We lay out the necessary steps for achieving this new operational mode in a double aberration-corrected instrument with uncorrected chromatic aberration and present preliminary experimental results in such mode.

1. Introduction
With the development of spherical aberration correctors for both transmission electron microscopy (TEM) and scanning transmission electron microscopy (STEM), the spatial resolution in 2D images has been dramatically improved [1]. The correction of spherical aberration allows a larger probe forming aperture to be used, which not only increases the lateral resolution, but also reduces the depth of field to a few nanometres [2]. This offers the feasibility of depth sectioning in similar fashion to confocal scanning optical microscopy (CSOM) [3]. Spherical aberration corrected TEM/STEM instruments fitted with two aberration correctors have been shown to be capable of working in this confocal mode, named as scanning confocal electron microscopy (SCEM) [4]. The theoretical calculation of the contrast mechanisms showed inelastic SCEM or energy-filtered SCEM (EFSCEM) gives much better depth selectivity and three-dimensional image contrast than elastic SCEM [5]. In particular the calculation showed that the 3D transfer function of EFSCEM does not have a ‘missing cone’, so that even laterally extended objects can be located in depth. Nellist et al. [6] have demonstrated a confocal optical configuration for elastic SCEM on Oxford-JEOL 2200MCO. The instrument is also fitted with an in-column $\Omega$ energy filter, allowing the possibility of EFSCEM experiments. However, chromatic aberration changes the focal length of a lens by $\Delta z = \Delta E_{\text{loss}} C_C / E_0$ for the inelastic electrons with an energy-loss of $\Delta E_{\text{loss}}$, relative to the elastically scattered electrons where $E_0$ is the accelerating voltage. Although spherical aberration correctors are becoming widespread because of their commercial availability, there is currently only one instrument fitted with a prototype chromatic aberration corrector because it is technologically much harder [7].

In this paper, we will present the 3D optical transfer function (OTF) of EFSCEM and list the steps necessary for achieving confocal electron trajectories suitable for EFSCEM in an instrument with
uncorrected chromatic aberration. This procedure allows the confocal point to be regained for the energy loss of interest. Furthermore, we will show preliminary results of EFSCEM from an extended object, an amorphous carbon film, as a proof of principle of the depth discrimination mechanism of the EFSCEM on an electron microscope.

2. OTF of Energy filtered SCEM

For a completely incoherent scattering object in the completely confocal situation with a point detector, the incoherent SCEM image intensity [6] can be written as the three-dimensional convolution

\[ I = \psi' \otimes PSF_{\text{confocal}} = \psi' \otimes \left[ |P_1|^2 |P_2|^2 \right] \] (2.1)

where \( \psi' \) is a local inelastic scattering potential and \( PSF_{\text{confocal}} \) is the inelastic confocal point spread function (PSF), a product of \( |P_1|^2 \) and \( |P_2|^2 \) (the PSFs of the illumination-side or imaging-side optics, respectively). \( PSF_{\text{confocal}} \) is only considered in an optical system using an infinitesimal energy-selecting window. In practice, a finite energy-selecting window \( \Delta E_{\text{window}} \) is normally implemented.

Typical energy filtered electron microscope images are recorded using electrons with energy losses that range over an energy window of several eV to ensure a high enough signal [8]. Therefore a defocus spread introduced to the imaging-side optics is given by a top-hat function \( S \) with width of \( \Delta E_{\text{window}} C \sqrt{E_0} \). So the PSF with a finite energy-selecting window is thus given by

\[ PSF_{\text{confocal}} = |P_1|^2 (|P_2|^2 \otimes S) \] (2.2)

where the convolution is along the z-direction.

The optical transfer function (OTF) is the 3D Fourier transform of the PSF. Figure 1 shows the OTFs for STEM a) and EF-SCEM with infinitesimal b) and 5eV c) energy-selecting window, respectively. With both SCEM modes the depth resolution is improved over STEM. The OTF for STEM has a missing cone region where no spatial frequencies can be transferred, whereas there are no such missing regions in the EF-SCEM, even with a 5eV energy window. This is important because laterally extended objects have many components at low radial spatial frequencies.

![Figure 1](image)

**Figure 1** Kx-Kz slices of the OTFs for STEM a) and EF-SCEM with infinitesimal b) and 5 eV c) energy-selecting window, respectively. The parameters for each calculation are for a double aberration-corrected instrument with an accelerating voltage of 200kV and a semi-angle of convergence of 22mrad.

3. Optical configuration setup for EFSCEM

Next we outline methods for establishing a confocal trajectory for energy filtered electrons with aberration-corrected illumination and imaging optics [9] in a single 200 keV instrument: the Oxford-
JEOL 2200MCO with an in-column \( \Omega \) energy filter [10]. The chromatic aberration coefficients in the pre- and post-specimen optics are \( Cc_1 \) 1.4mm and \( Cc_2 \) 1.43mm [11]. Hexapole-based correctors [12] also contribute a positive value to \( Cc \), and hence the overall value of \( Cc \) is increased over that of an uncorrected lens.

Establishing confocal trajectories for elastic electrons requires the simultaneous tuning of both correctors about a mutual optical axis. Both correctors need to be aligned so that the upper column optics and lower one are confocal at the point A in figure 2 a). The details of this procedure can be found in Ref [6]. A typical elastic probe image formed through vacuum is shown as in figure 3 a). To regain the confocal point for the inelastic electrons (with a desired energy loss of \( \Delta E_{\text{loss}} \)), we keep the optical alignment for the elastic electrons intact and simply increase the accelerating voltage \( E_0 \) by a factor \( k \) times the energy-loss of interest \( \Delta E_{\text{loss}} \) where \( k = Cc_2 / (Cc_1 + Cc_2) \). The pre-specimen optics, due to its chromatic aberration \( Cc_1 \), now focuses the electrons of the second incidence energy onto the point C, distant from A by \( k\Delta E_{\text{loss}} Cc_1 / E_0 \) shown in figure 2 c). After the energy-loss event, the electrons have an energy of \( E_0 + (k - 1)\Delta E_{\text{loss}} \) and the formula for \( k \) given above ensures that the electrons are accurately focussed by the post-specimen optics onto the selecting collector aperture. This optical configuration is kept fixed and the specimen brought down to the confocal point C using z-stage in figure 2 c). Finally, the post-specimen optics are switched into the spectrum mode and the energy-selecting slit with the size of \( \Delta E_{\text{window}} \) is centred at the energy loss \( \Delta E_{\text{loss}} \) of interest using an in-column \( \Omega \) energy filter. On returning the post-specimen optics to imaging mode, the entire microscope is reconfigured into a confocal condition for the inelastic electrons with energy loss of \( \Delta E_{\text{loss}} \).

**Figure 2** Schematic diagram of the confocal trajectories for elastic SCEM

\( a) \), which shows the beams (-----) away from the confocal point A are rejected by the collector aperture, and \( b) \), which shows the post-specimen optics, due to its chromatic aberration focuses the beams (----) with the energy loss of interest \( \Delta E_{\text{loss}} \) are focused at the point B. The diagrams \( c) \) shows an increment of \( k\Delta E_{\text{loss}} \) applied to the accelerating voltage \( E_0 \) can regain A new confocal point C for the beams (----) with the energy loss of interest \( \Delta E_{\text{loss}} \).

Figure 3 b) and c) shows the inelastic probe image observed in the collector aperture plane formed though an amorphous carbon thin film recorded on a Gatan CCD with 5 eV energy selecting window placed at 290 eV when the specimen sits at the confocal point and at 164 nm away from it, respectively. It is clear to see that the signal largely drops off at the centre of the probe image when the specimen moves away from the confocal point. This experimentally demonstrates that the scattering from points away from the confocal point become out-of-focus at the collection plane. By placing a pinhole at the collection plane, it is feasible to reject or detect less strongly the out-focus scattering than the in-focus scattering. With a high resolution stage-scanning or beam scan-descan system, we can collect the intensity passing through the pinhole while the specimen is moved with respect to the confocal point. As a result, a 2D elemental map can be acquired with a transverse section at any depth.
in a thick specimen and a 3D elemental distribution accordingly can be formed by stacking a series of the 2D maps. EFSCM has the potential to be a powerful 3D chemical analysis technique at a nanometre-resolution, an entirely new form of electron microscopy.

**Figure 3** a) shows experimental images of the probe in the elastic confocal mode formed through vacuum and b) through a carbon film in the EFSCM mode with 5eV energy filtering window placed at the carbon K-edge, when the film is just at the confocal point and c) a point of 164nm away from it, respectively.

4. **Conclusion**

We showed that EFSCM with a 5eV energy-selecting window has no missing cone region in its OTF. We devised a technique whereby the instrument is aligned for the inelastic electrons via increasing the accelerating voltage by a factor $k$ for the energy-loss of interest. We demonstrated experimentally the depth discrimination mechanism in the EFSCM mode on an electron microscope.

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**References**