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Measurement of the Point Spread Function for Low-Loss Inelastic Scattering

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The delocalization of inelastic scattering is described by a point spread function PSF(r) that represents the scattering probability as a function of the distance r from the trajectory of an incident electron. For core-loss scattering, the PSF has sub-nm or even subatomic dimensions but for low-loss scattering (energy loss E < 50 eV) its width can be several nm or tens of nm. This width determines the spatial resolution of TEM-image features that arise from inelastic scattering, and partially determines the minimum line-width achievable in electron-beam lithography [1] or e-beam deposition [2,3].

Quantum dipole theory gives PSF ~ $[K_1(r/b_{max})]^2 + [K_0(r/b_{max})]^2$ with $b_{max} = 1/(k_0\theta_E)$. Fourier transform of the angular distribution of the inelastic scattering amplitude gives PSF ≈ $[b_0^2/(r^2+b_0^2\ )] \exp(-r/b_{max})$ with $b_0 \approx 1/(2k_0\theta_c)$. Both expressions yield very similar results for $r > b_0$ but the second version avoids a singularity at $r = 0$ by including a cutoff in the angular distribution of intensity at $\theta_c = (2\theta_E)^{1/2}$. But doubt remains about the most appropriate value of b_0 [4], which is perhaps best resolved experimentally.

Measurement of the PSF is possible by recording a sub-nm probe (focused on a thin specimen) through an imaging filter (*e.g.* Gatan GIF). The specimen should be thin enough to avoid significant beam broadening, and aberrations of the probe-forming and imaging lenses must be minimized [4]. Our procedure has been to focus and aberration-correct the objective and condenser lenses with the GIF set for zero loss, then increase the TEM high voltage by a few eV and refocus the condenser system for minimum image width (if necessary) before recording the probe image at high magnification.

Results are shown in Figs. 1 and 2. The measured PSF approximates to $1/r^2$ for $r > 0.1$ nm, as expected. The full width at half maximum (FWHM) exceeds $2b_0$, likely due to a change in phase or incoherency of the inelastic scattering at higher angles [4]. For $E < 5$ eV, the estimated median delocalization diameter is about 60% of that given by the approximate formula: $d_{50} \approx 16\text{nm}/E^{3/4}$. For $E > 5$ eV, our measured FWHM and d_{50} values start to increase with increasing energy loss, suggesting that chromatic aberration is interfering with measurement at these higher values of energy loss [5].

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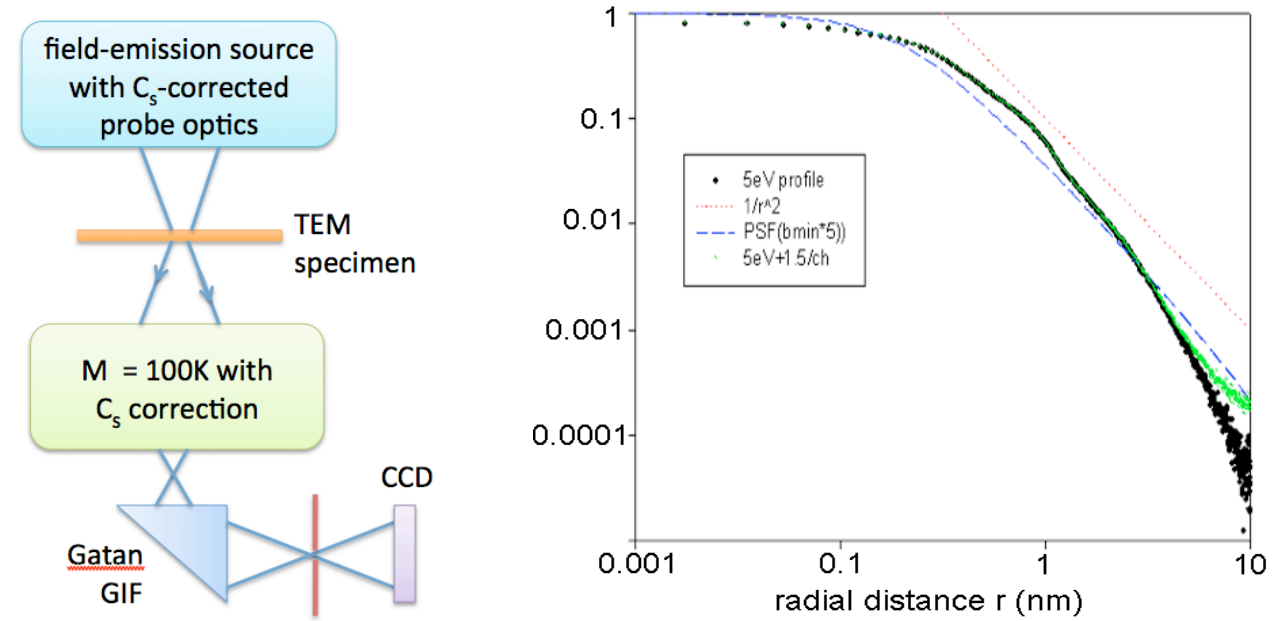

Figure 1. Left: measurement scheme schematic. Right: Inelastic-scattering PSF as measured (black data points) and with background correction (green data points) together with a PSF calculated using the Lorentzian formula (blue dashed curve) and compared with a $1/r^2$ dependence (dotted red line).

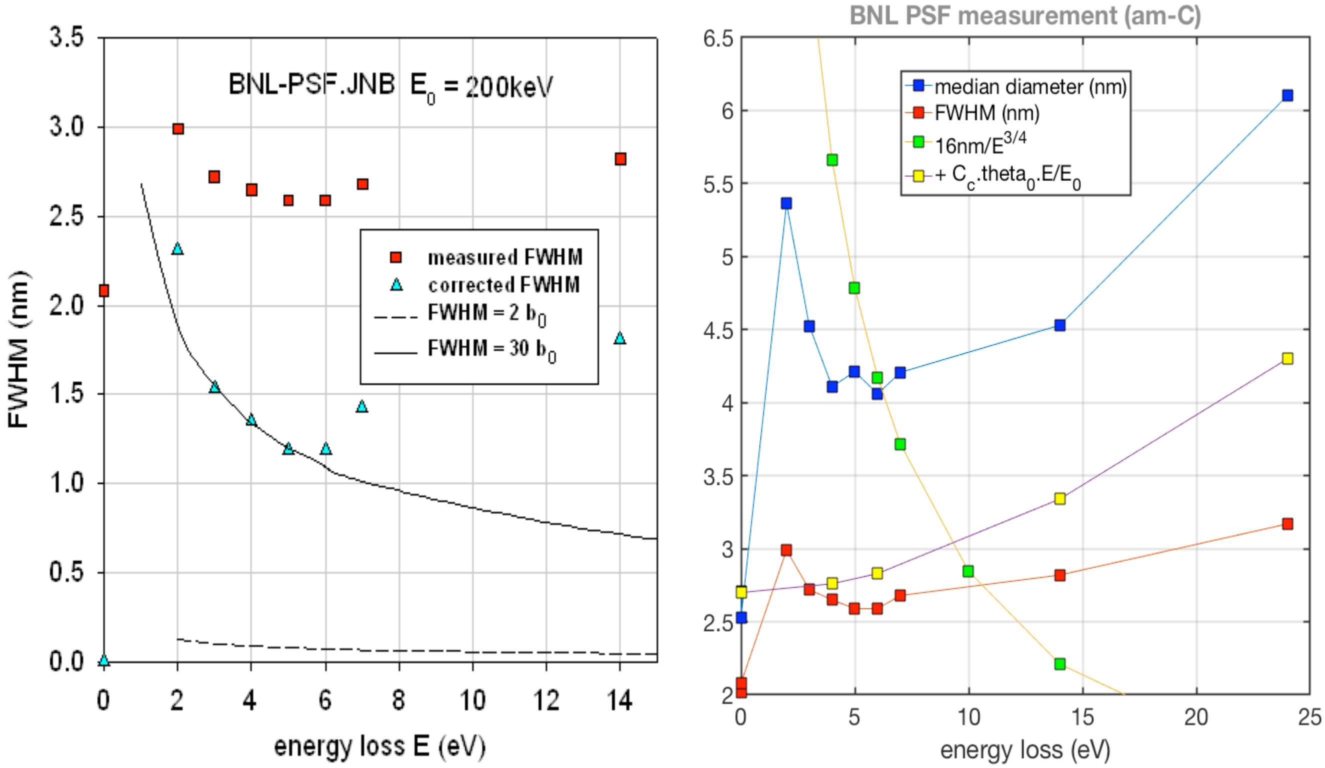

Figure 2. Left: FWHM before and after correcting for 0-eV probe diameter, compared with two estimates based on theory. Right: measured median diameter (blue squares) compared with 16nm/$E^{3/4}$ (descending curve, green squares). The two lower curves show the measured FWHM (red squares) compared with a schematic estimate of chromatic aberration (yellow data points).