The balancing act between resolution and sensitivity in DPC-STEM

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As microscopists, we are constantly seeking to observe smaller and smaller details in our samples. As scientists, we strive to determine subtle features of specimen properties with good sensitivity (such as the inbuilt electric [1] and magnetic fields [2], or the number of atoms in a column [3]). As realists, we note that these aims sometimes conflict. In this presentation, we will map out the limits of resolution and sensitivity within the context of differential phase contrast scanning-transmission electron microscopy (DPC-STEM) imaging of nanoscale electromagnetic fields in materials.

Recently, we demonstrated in low-resolution DPC-STEM that the improvement of image resolution with increasing convergence angle is a non-trivial process - the broad tails of an Airy probe interact with specimen regions far from the central lobe of the electron probe (illustrated in Fig 1). These broad tails interfere with the central intensity lobe as the beam propagates to the detector plane. This interference can cause significant deviations from the classical geometrical optics description, forming sharp peaks and troughs - without producing a clear shift of the disc across the detector. These effects need not necessarily reduce measurement reliability. Using a modern pixel detector, an accurate measurements can be made through measurement of the centre of mass [2], though it involves collecting a vast amount of data relative to the simple information we seek. Alternatively, using the large segments of a typical segmented detector carefully one can integrate over the peaks to obtain a rather accurate phase measurement with only a few data points per pixel. To further ameliorate this problem, beam shaping methods can be applied [4] (illustrated in Fig 2).

Resolution improvement in DPC-STEM describes only one side of the imaging coin - a typical high-resolution image may still lack desired specimen information due to low sensitivity, and so we must ensure sensitivity is not lost too severely when increasing resolution. Given that images are formed of a finite number of electrons, each bright-field disc has a certain level of fundamental shot-noise present. This leads to an uncertainty in the measured centre of mass, limiting our ability to reliably detect small changes in specimen phase gradient. We will describe how the related optical parameters limit our phase-gradient-sensitivity, and routes to improve the sensitivity of DPC-STEM. By carefully combining resolution and sensitivity studies of DPC-STEM imaging, we hope to prescribe optimal optical settings for the desired nanoscale field mapping [5].

[1] Brown, H. G., et al. "Measuring nanometre-scale electric fields in scanning transmission electron microscopy using segmented detectors." *Ultramicroscopy* 182 (2017): 169-178.

[2] Krajnak, M., et al. "Pixelated detectors and improved efficiency for magnetic imaging in STEM differential phase contrast." *Ultramicroscopy* 165 (2016): 42-50.

[3] LeBeau, J. M., et al. "Standardless atom counting in scanning transmission electron microscopy." *Nano Letters* 10.11 (2010): 4405-4408.

[4] Clark, L., et al. "Probing the limits of the rigid-intensity-shift model in differential phase contrast scanning transmission electron microscopy", *Submitted, arXiv: 1801.07572.*

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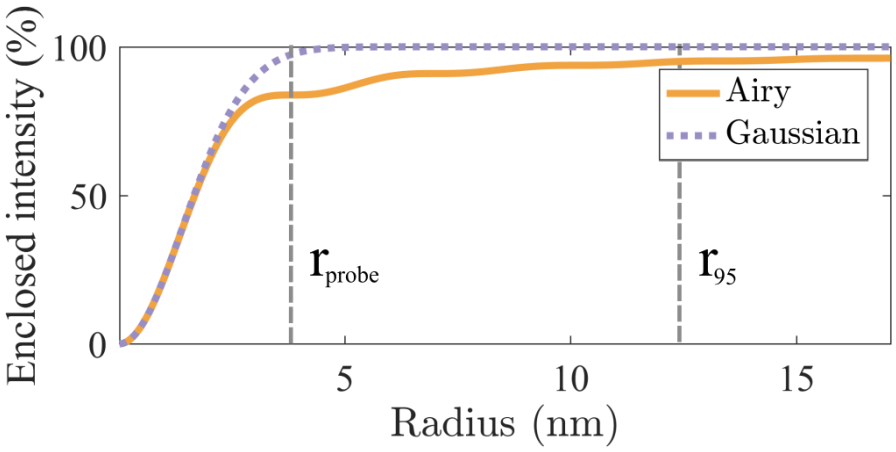

Figure 1: The Airy probe is significantly more delocalised than a Gaussian of the same FWHM.

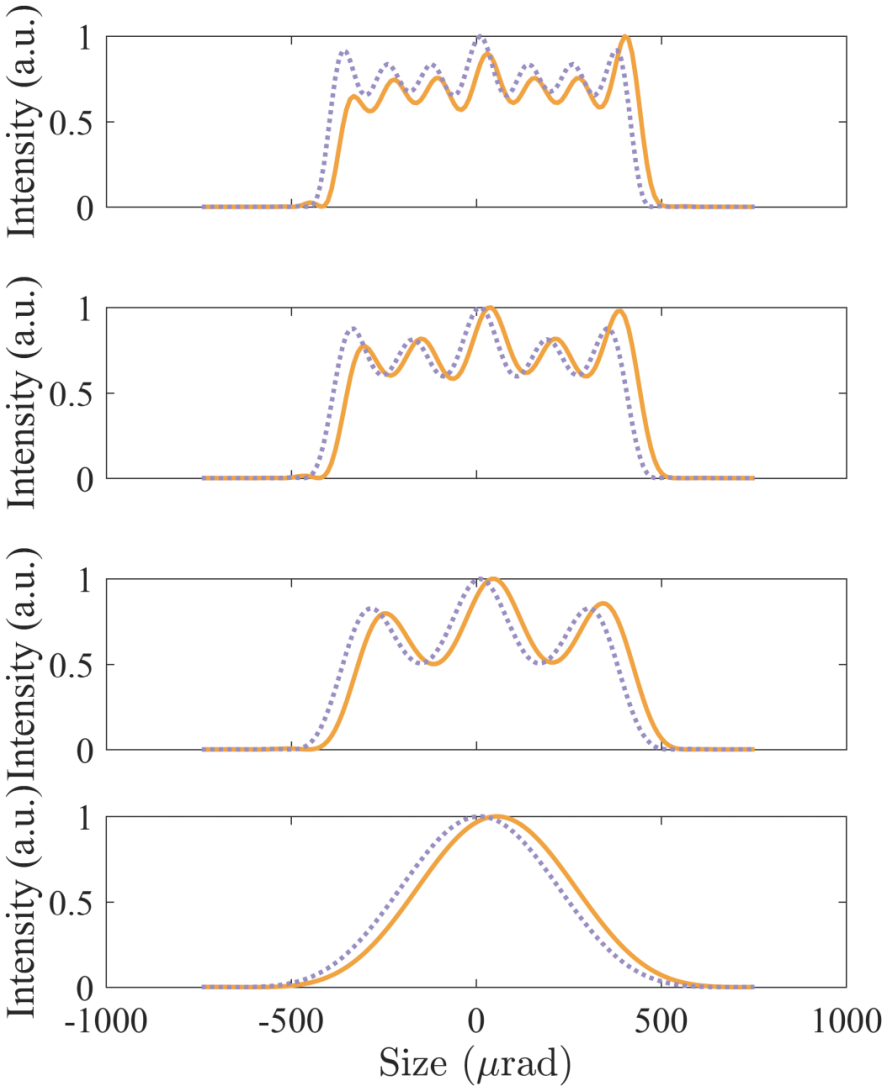

Figure 2: Probe reshaping may enable the rigid disk model to hold for a greater range of specimens than the standard probe. (a)-(d) probe apodisation at 7th, 5th, 3rd, 1st Airy minimum).