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Automated Design of Electron Mirrors for Multipass Electron Microscopy and 4D-STEM+EELS

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Dose-efficient imaging techniques are critical for understanding the structure and properties of low-atomic-number materials. Two very different techniques—multipass electron microscopy [1] and four-dimensional scanning transmission electron microscopy [2] with simultaneous electron energy loss spectroscopy (4D-STEM+EELS)—that allow for increased information at constant electron dose stand to benefit or depend on a single, relatively new electron optical component: a gated mirror [3] that can selectively transmit or reflect electrons.

Multipass electron microscopy improves contrast by passing electrons through the sample multiple times in order to increase the phase and amplitude modulation of the transmitted electron produced by a specimen. Several designs have been proposed [4]–[7] and manufacturing is in progress for one microscope [5]; the use of a gated mirror to pass electrons in from the source or out to the detection apparatus is one of several approaches to handle switching between multipassing and electron emission/detection [3]. An important parameter for a gated mirror in multipass electron microscopy is the spherical aberration, as electrons reflected in the diffraction plane can acquire a negative third-order spherical aberration to cancel the positive spherical aberration of other elements in the column and lead to much lower aberrations added on each pass, allowing for a higher number of passes at high resolution without deterioration of image quality.

The spread of fast cameras has spurred a wave of development in four-dimensional scanning transmission electron microscopy (4D-STEM), where a diffraction pattern is recorded at each probe position in scanning transmission electron microscopy (STEM). Many 4D-STEM techniques are dose-efficient and can offer a wealth of information about low-atomic-number materials. One drawback of 4D-STEM as compared to use of the high-angular dark field detector is that the unscattered electron beam is fully blocked by the camera, so simultaneous recording of electron energy loss spectra (EELS) is not possible. It may still be possible to extract meaningful information from a 4D-STEM dataset recorded by a camera with a hole in it [8], but higher dose-efficiency is possible if inelastically scattered electrons can be separated before electrons strike the fast camera. A gated mirror may make this possible with a gate voltage set to pass the unscattered beam and reflect inelastically scattered electrons.

To design mirrors suitable for these two techniques, we developed a routine to automate the design of several electron optical components using Munro’s Electron Beam Software [9]. We used a Nelder-Mead simplex to simultaneously optimize the shape of the mirror electrodes, the electrode voltages, and the crossover position at the entrance of the mirror to achieve a specified third-order spherical aberration. We used a similar approach to optimize ray retracing, which is a necessary condition for multipass electron microscopy—retracing prevents the beam from shifting or defocusing with respect to the specimen between passes. An example mirror for 30 keV electron energy with C_3 = 15.26 mm and optimized retracing for multipass electron microscopy is shown in Figure 1.

This versatile automated optimization approach allows for design of mirrors over a wide range of energies that are suited for two distinctly different new dose-efficient electron imaging techniques [10].

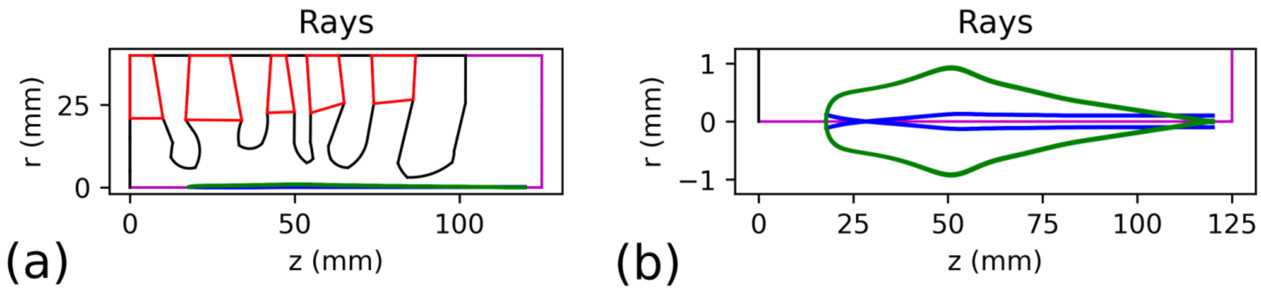

Figure 1. Mirror for 30keV electron energy, with a hole for voltage gating. Retracing is optimized for multipass microscopy. (a) Shows the electrodes (black), dielectric (red) and rays (blue and green). (b) Magnified image of the rays from (a).

References:

[1] T Juffmann et al., Sci Rep **7** (2017). doi: 10.1038/s41598-017-01841-x
[2] C Ophus, Microscopy and Microanalysis **25** (2019), p. 563. doi: 10.1017/S1431927619000497
[3] BB Klopfer et al., Review of Scientific Instruments **92** (2021), p. 043705. doi: 10.1063/5.0039523
[4] P Kruit et al., Ultramicroscopy **164** (2016), p. 31. doi: 10.1016/j.ultramic.2016.03.004
[5] SA Koppell et al., Ultramicroscopy **207** (2019), p. 112834. doi: 10.1016/j.ultramic.2019.112834
[6] M Turchetti et al., Ultramicroscopy **199** (2019), p. 50. doi: 10.1016/j.ultramic.2019.01.010
[7] BB Klopfer and MA Kasevich, arXiv:2107.04707 [physics] (2021), Accessed: Feb. 23, 2022. http://arxiv.org/abs/2107.04707
[8] B Song et al., Phys. Rev. Lett. **121** (2018), p. 146101. doi: 10.1103/PhysRevLett.121.146101
[9] EMDesign Github repository, https://github.com/tylerharvey/EMDesign. Accessed: Feb. 24, 2022.
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