A Low-Energy Counting Electron Spectrometer Integrated into a Scanning Electron Microscope

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Electron spectroscopy is a powerful tool in electron microscopy, with wide-ranging uses throughout material science and engineering. In the last decade, its application has become of interest to physicists as well, first with the its use in photon-induced near-field electron microscopy (PINEM) to image nanoscale optical fields[1], and more recently in combination with optical cavities to create heralded, and potentially quantum, free-electron sources[2]. This work has largely been limited to (scanning) transmission electron microscopes ((S)TEMs), with electron energies on the order of 100 keV or more. This is due to the fact that commercially available spectrometers are only available for these energies.

There is much interest in exploring these phenomena at the 1-10 keV energy range found in scanning electron microscopes (SEMs) and electron lithography tools[3]. In this work, we design, construct, and test a low-energy counting electron spectrometer for this purpose. The apparatus, as illustrated in Fig. 1, is designed to be integrated into a door stage in our SEM tool to enable low-energy (S)TEM-like measurements and has demonstrated its basic operation at 10 keV. A sample image of the dispersed beam for various input energies is shown in Fig. 2. By introducing a slit and electron counter, we can measure the electron to ~0.2 eV energy and nanosecond temporal resolution.

Through this work, we aim to take the powerful tool of electron spectroscopy from TEM to SEM energies in order to study electron-photon interactions at significantly reduced energies than previous studies. This ability might also lend itself to lower energy characterization of 2D materials, the creation of heralded free-electron sources for microscopy and lithography, and allow for the miniaturization and more widespread adoption of PINEM and energy-loss spectroscopy techniques.

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[1] B. Barwick, et al. "Photon-induced near-field electron microscopy" *Nature*. 462 (7275): 902-906

[2] Feist et al. "Cavity-mediated electron-photon pairs" *Science* 377, 6607 (2022): 777-780

[3] Shiloh, R. et al. "Quantum-coherent light-electron interaction in a scanning electron microscope." *Physical Review Letters* 128, no. 23 (2022): 235301.

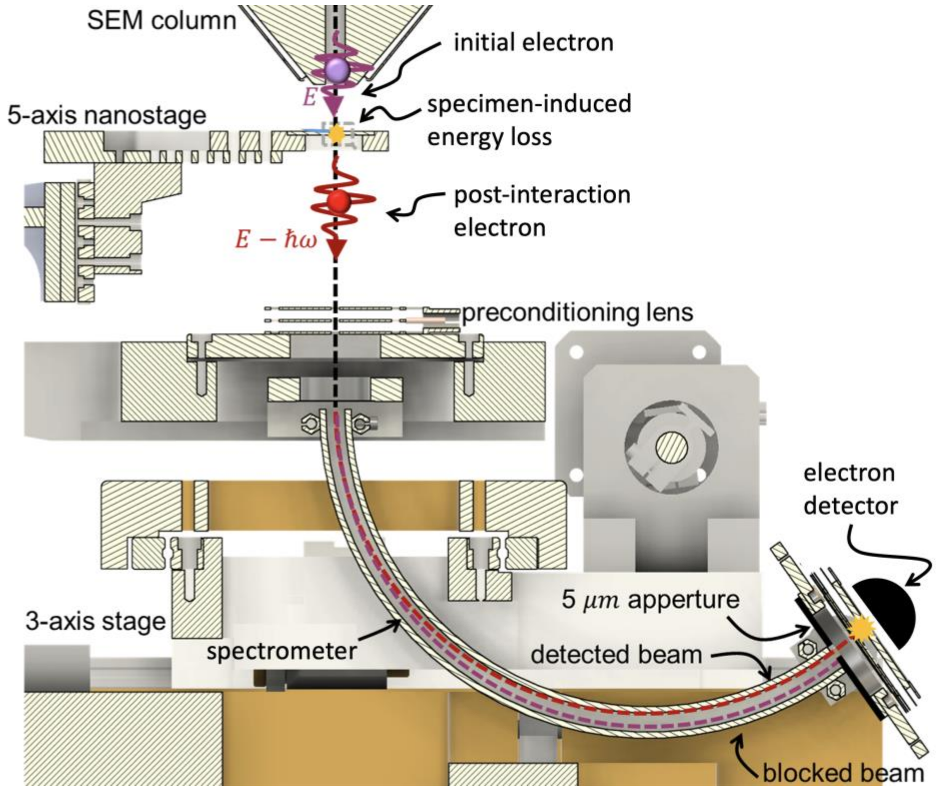

Figure 1: Electron spectrometer integrated into the SEM chamber stage: First, the electron passes nearby our sample, held in a 5-axis nanostage. After interacting with the sample, the beam is refocused into our spectrometer with an Einzel lens, which is aligned by motion of a 3-axis door stage. If the electron has lost energy, it is bent more strongly in the spectrometer and is picked up by a direct electron detector. The slit and detector can be interchanged with a camera and phosphor system, which produced the results of Fig. 2.

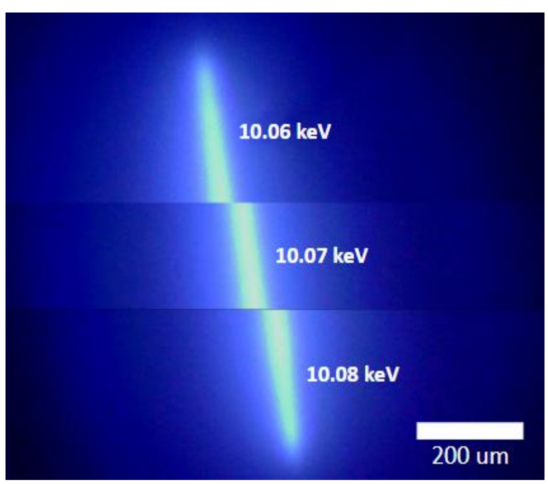

Figure 2: Demonstration of spectrometer performance at around 10 keV, demonstrating its dispersion: This was captured with a vacuum-integrated CCD imaging a phosphor plate. In our beam energy range, the measured dispersion of 25 μm/eV gives ~ 0.2 eV energy resolution when incorporating a 5 μm slit.