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# Electrostatic Switching for Spatiotemporal Dose Control in a Transmission Electron Microscope

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Transmission electron microscopy (TEM) has reached a point where our ability to extract information from materials is limited more by the samples than by the microscope. Modern high-brightness guns and aberration-corrected optics can direct immense current densities onto samples, yielding extraordinary resolution, precision, and analytical detail, but only if the sample can survive. It is now widely recognized that progress depends on making the best use of electron dose. This means exposing the samples with spatiotemporal modulation designed to minimize the effects of beam damage, and it also means using automation, adaptive sampling, and advanced reconstruction algorithms to maximize the information return per probe electron.

We will present an electrostatic dose modulation (EDM) system that uses nanosecond-scale pulse width modulation (PWM) to control exactly when the electron beam is reaching the sample. EDM avoids the low speed and hysteresis problems associated with magnetostatic beam blanking. Coupled with a highly programmable timing control system, the EDM can operate in several modes, and even more than one mode simultaneously. EDM can:

- replace the slow (millisecond-scale) magnetostatic beam blanker used for exposure control in many microscopes, allowing high-quality short single-shot exposures
- allow users to quickly adjust the electron beam current over a wide range without affecting focus or alignment
- automatically shut off the beam during dead times such as flyback between lines and frames in scanning TEM (STEM), or when the STEM system is not actively recording data
- eliminate blur during preprogrammed deflection or focus-change sequences by blanking the beam during the transient response of the magnetostatic elements
- eliminate rolling-shutter artifacts by synchronizing the PWM with the TEM camera readout
- using a custom FPGA system, listen to the timing signals from a STEM controller and adjust the intensity independently in every single pixel, allowing arbitrary mask patterns to be impressed on the sample for region-dependent dose control and/or lithography

We will show examples of all these operating modes, highlighting both current capabilities and plans for the future of the technology.

The system can be operated directly through a user-friendly interface, and it can also be automated through an open software interface. In the future, this automation interface could be used for rapid adaptive dose control, using the information from each acquisition to decide exactly where to allocate the dose for the next scan. Coupling this with advanced reconstruction algorithms derived from compressive sensing and machine learning, the system has the potential to automatically maximize the relevant information return while minimizing damage to the sample.

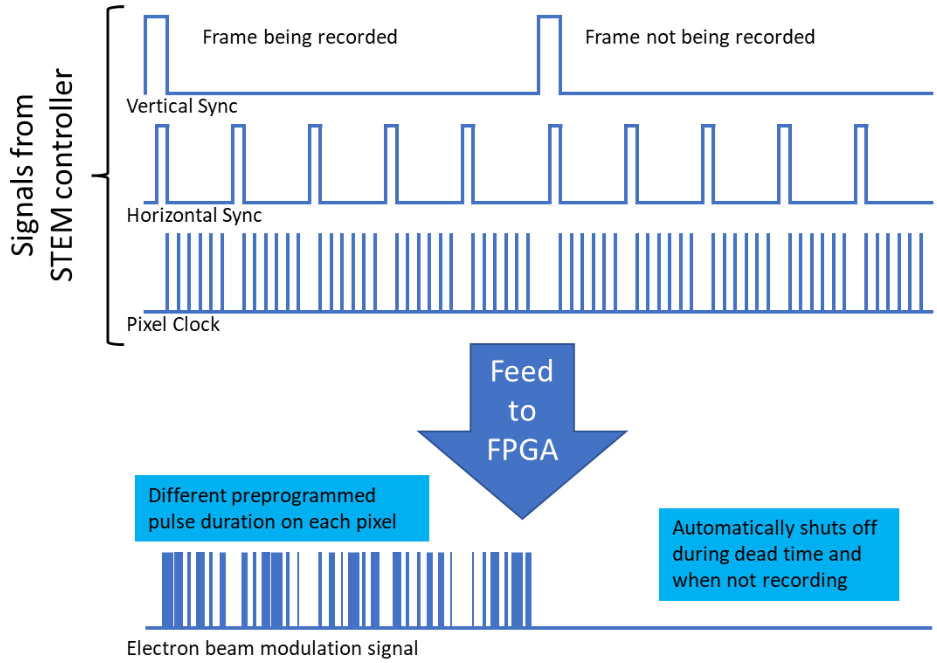


**Figure 1.** How the timing system synchronizes the PWM with the STEM scan to independently modulate the dose in every pixel while minimizing dead time between scan lines, frames, and acquisitions

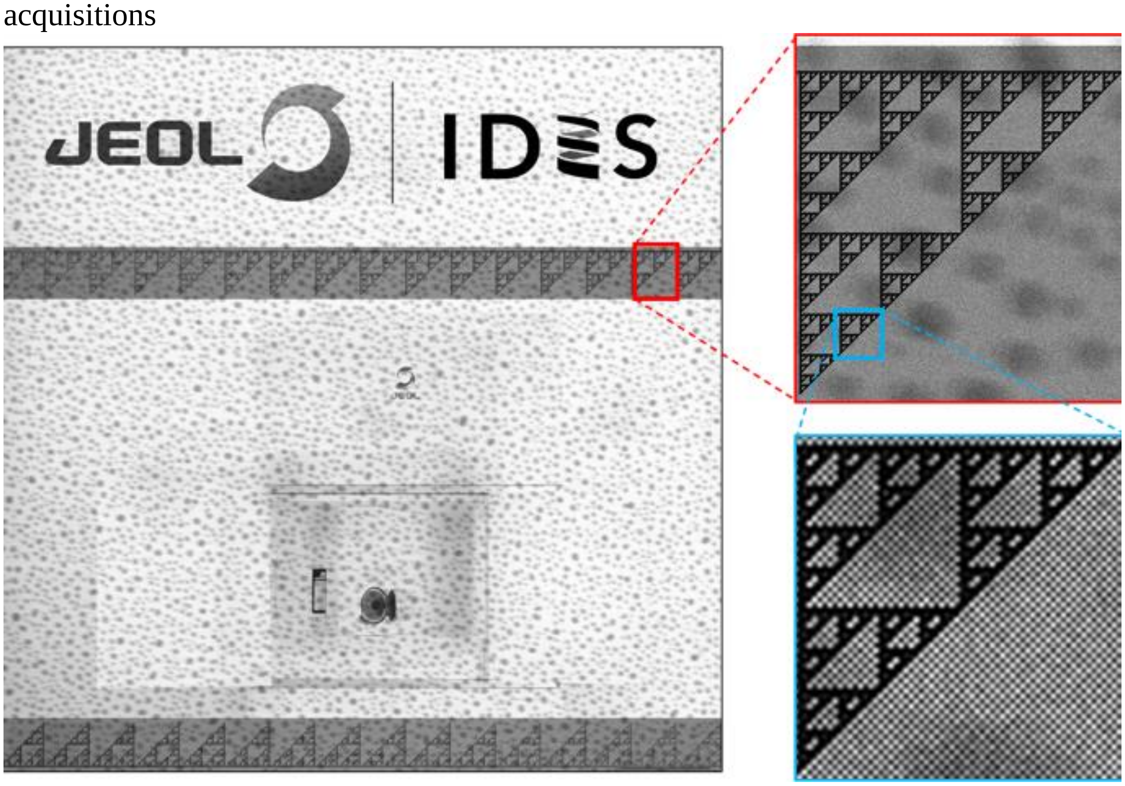


**Figure 2.** Arbitrary dose modulation applied to a STEM scan of Au nanoparticles. This is raw, as-measured data. The logos, fractal patterns, and photograph were impressed on the scan using the dose modulation system. Acquired in collaboration with the Rosalind Franklin Institute, UK.

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