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The 4D Camera – An 87 kHz Frame-rate Detector for Counted 4D-STEM Experiments

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The advent of direct electron detectors has provided electron microscopy with much more sensitivity and speed enabling a whole new set of imaging modalities. In scanning transmission electron microscopy (STEM), capturing the full 2D convergent beam electron diffraction pattern at every scan position in a 2D raster scan produces 4D datasets which can be utilized to create traditional STEM images with variably defined collection angles post-acquisition as well as new 4D-STEM techniques such as center-of-mass [1], ptychography [2], nanoscale strain mapping [3], STEM holography [4] and many other novel modalities. Essentially, the microscopist acquires almost all of the scattering data and can then determine the useful image contrast mechanisms during post-processing utilizing 4D-STEM techniques. [5]

Pixelated diffraction detectors are now available commercially from several vendors, but are typically limited to approximately 1 millisecond (1 kHz) frame rates [1], which is much slower than the 10 microsecond dwell time typically used with traditional, monolithic (e.g. annular dark field) STEM detectors. These slower speeds limit the application of 4D-STEM in experiments where researchers desire to utilize experimental parameters similar to the doses, scanning speed, drift rates and fields-of-view offered by traditional STEM imaging. The 4D Camera, designed and installed at Lawrence Berkeley National Laboratory, acquires full 4D-STEM maps within seconds rather than minutes.

In this presentation, we describe the operation and applications of the 4D Camera, a CMOS active pixel sensor [6] with 576x576 10µm pixels back-thinned for high performance at accelerating voltages from 30kV to 300kV. The full detector is read out at 87,000 frames per second (11 µsec) producing an approximately 480 Gbit/s data rate. The data is streamed from the camera head to four field programmable gate arrays (FPGAs) which packetize, arrange and stream the data to the RAM of four dedicated receiver PCs (Figure 1a). Once safely in memory, the data is transferred to flash storage on a fifth analysis PC. Feedback to the user on data quality of the initially 150 - 650 GB can be provided within a few minutes by basic edge computing algorithms.

Data reduction by electron counting [7] occurs by open source python/C++ algorithms called *stempy* [8] developed for rapid 4D-STEM processing and analysis. The resulting sparse electron counted datasets (Figure 1b, c) achieve approximately 100x reduction in data size compared to the dense form of the frames making processing of even 1024x1024 4D-STEM scans capable of fitting in RAM of moderately powerful desktops and laptops. Further, the data is uploaded to the NERSC high performance computing center where processing is done in the cloud using shared Jupyter Notebooks. The camera has been in operation on the TEAM 0.5 at full speed since January 2020 and has since been used to image several scientifically relevant materials such as full battery stacks and superlattice multi-layers (Figure 1 d, e). Still further improvements to the detector system will include addition of a set of 16 diode rings as a segmented

HAADF detector for high angle scattering beyond the central CBED pattern allowing simultaneous acquisition of high- and low-angle scattering regardless of the STEM camera length. Also planned is more direct data streaming to the National Energy Research Computing Center (NERSC) over an up to 400 Gbit connection provided by NERSC for ease of data access, computation, analysis and storage. Implementation of parallelized advanced algorithms such as ptychographic reconstruction are then possible with rapid feedback to the user. [9]

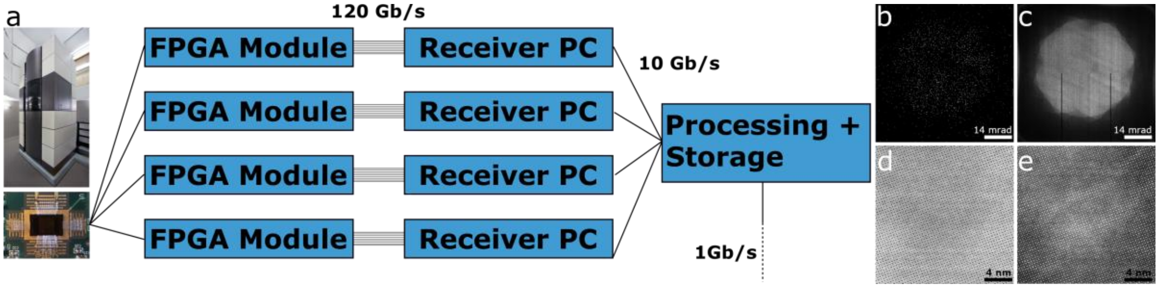

Figure 1. a) Edge compute system for detector acquisition, storage and analysis at the microscope. The detector streams raw data to 4 receiver PCs which saves the data on a 5th PC for analysis and storage. b) A single detector frame with single electron counts. c) Summation of 1000's of counted frames showing a CBED pattern of a converged probe. c) BF-STEM and d) ADF-STEM images constructed from the electron counted data set of a SrTiO3 / PbTiO3.

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[8] https://github.com/OpenChemistry/stempy
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