HOW TO MAKE 4D STEM ACCESSIBLE TO EVERYONE:

Overcoming 4 common problems that stop scientists from using the 4D STEM technique

Within microscopy, 4D STEM can often be seen as a promising, yet complex technique. If you are finding yourself shying away from 4D STEM because of the technical challenges that can come along with it, you are not alone! We've narrowed down 4 of the most common issues that prevent researchers from getting the most out of 4D STEM and identified a few common solutions that may just make your 4D STEM workflow a whole lot less complicated!

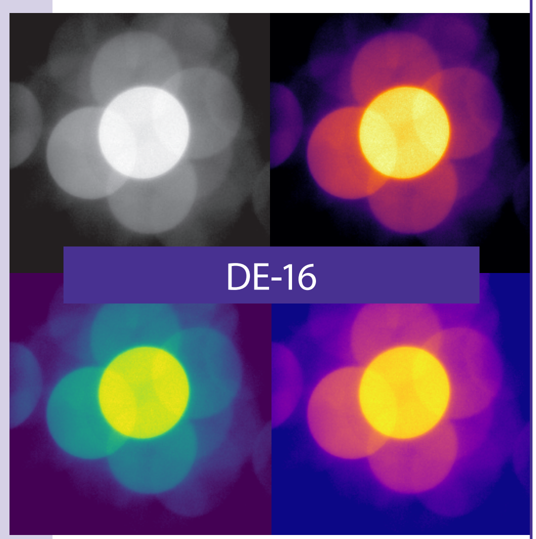
ISSUE #1: FLYING BLIND

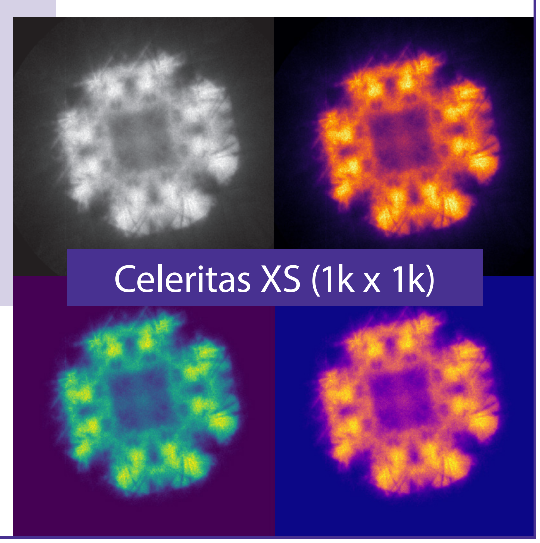
When operating in 4D STEM mode, the camera is collecting diffraction patterns (CBED images). While each of these contains a lot of valuable information, the CBED images are not easily interpretable on their own. A real-space image of the specimen is required to answer basic questions such as "Am I collecting data from the right location on the sample (or has the position drifted)?", or "Is the sample in focus?"

Early 4D STEM acquisition software often lacked the ability to generate such images, leaving users essentially blind when acquiring data. Users may not notice an error with the data collection until after they have processed the data, a process which could take minutes, or even hours.

Keeping up-to-date acquisition software with real-time virtual image generation is the solution. Always check for updates from your camera's manufacturer. Open source initiatives, such as LiberTEM-Live, offer one solution for seeing a live preview image of your sample. For those who have a CEFID energy filter, the CEOS Panta Rhei software offers 4D STEM acquisition tools for a range of compatible cameras.

At DE, know how common this issue is so we've also developed our own software to tackle the problem. Direct Electron's Mission Control + Dimension software includes integrated control of the detector (e.g. Celeritas XS) and the DE-FreeScan scan generator, and includes the ability to rapidly process 4-dimensional datasets via a powerful GPU. This allows for real-time generation of virtual images from the 4D dataset during acquisition, providing instantaneous, inter-pretable feedback. This makes 4D STEM data acquisition simple and straightforward.





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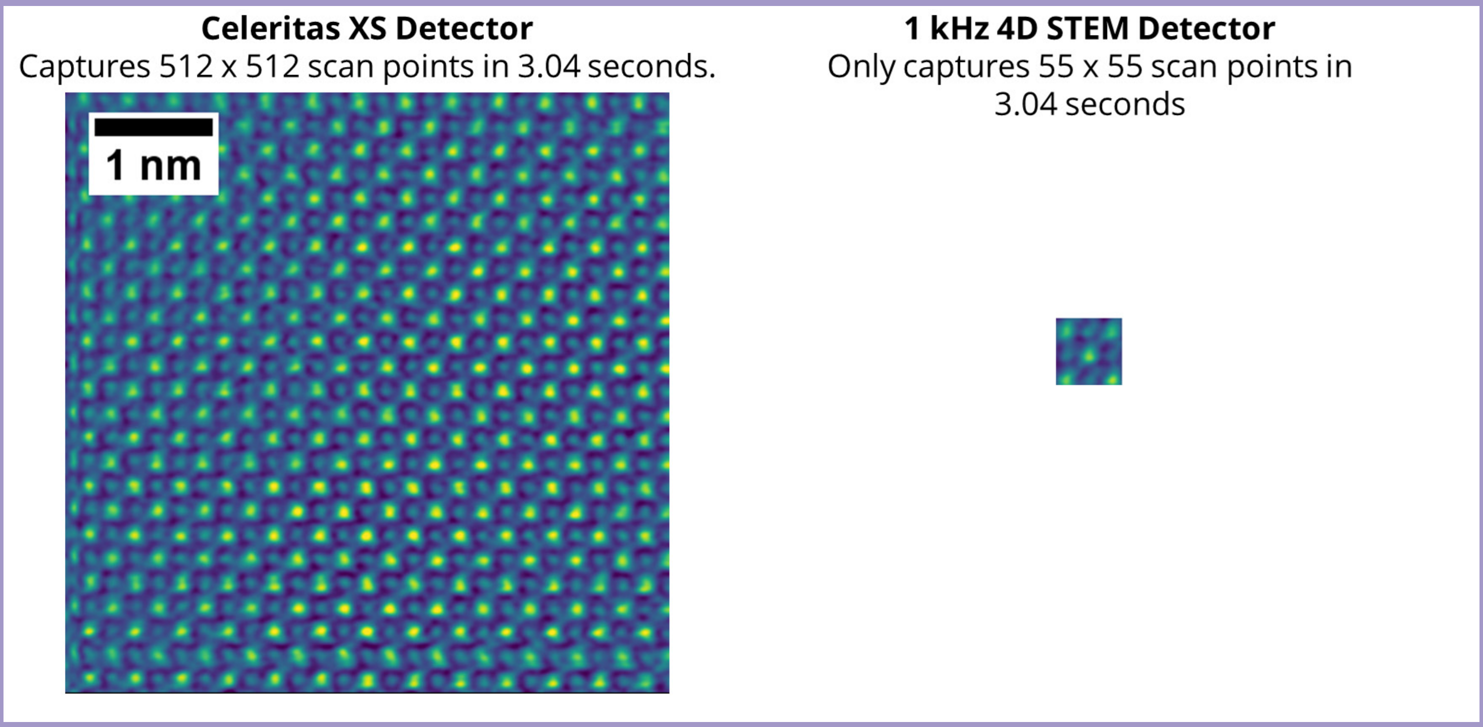
4 WAYS TO MAKE 4D STEM ACCESSIBLE TO EVERYONE

ISSUE #2: 4D STEM IS SLOWER THAN CONVENTIONAL STEM

In 4D STEM, each image recorded by the camera represents just one probe position in the STEM scan. This means that even very fast detectors struggle to generate 4D STEM datasets at a practical speed. A 4D STEM detector operating at 1000 fps may sound fast, but when you consider a scan region with 1k x 1k probe positions, that is one million scan points! At 1000 fps, with one image per scan point, that will take almost 17 minutes. And scanning larger regions takes even longer!

Not only does this consume a lot of instrument time, the sample may drift out of position, or out of focus during the acquisition. Many cameras are just too slow to be practical for many 4D STEM experiments.



An increase in detection speed can often be gained with a different camera or sometimes cameras can even see improved performance with a simple firmware and software update! Don't forget to always check for the latest updates for your equipment. Our very own DE-16 (one of our older cameras) is able to reach speeds of over 8000 FPS with a firmware update!

If you still need more speed, the latest generation of 4D STEM cameras are capable of imaging speeds of over 10,000 frames per second. This is an order of magnitude faster than earlier 4D STEM detectors. This can also help to prevent or limit sample damage that occurs at lower imaging speeds.

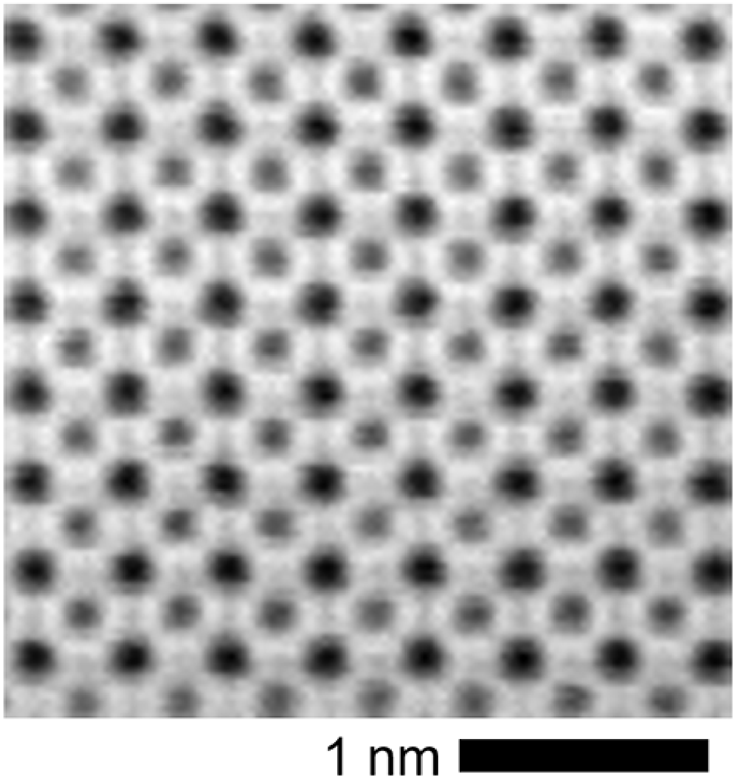
We build our cameras to be fast too: Direct Electron's Celeritas XS detector allows users to choose different readout areas, each of which has a fast readout speed. At its fastest, the detector can collect data at up to 87,000 fps. This is equivalent to a dwell time of 11.6 μs dwell time per probe position, which approaches the speed of conventional 2D STEM imaging.

ISSUE #3: BRIGHT CENTRAL SPOT = DETECTOR DAMAGE

When operating in 4D STEM mode, the detector is collecting diffraction patterns (CBED images). This means that part of the detector, normally the center, is frequently exposed to a very bright disc or spot of illumination, and thus receives a significant electron dose.

The bright spot is being swept very rapidly over the sample, so it doesn't dwell in the same place on the sample for very long (less than a millisecond). However, the bright spot stays in roughly the same place on the camera for the whole 4D STEM acquisition (tens of seconds or minutes). So the bright central spot is specifically a problem for damaging the camera's sensor, if the sensor is not radiation hardened.

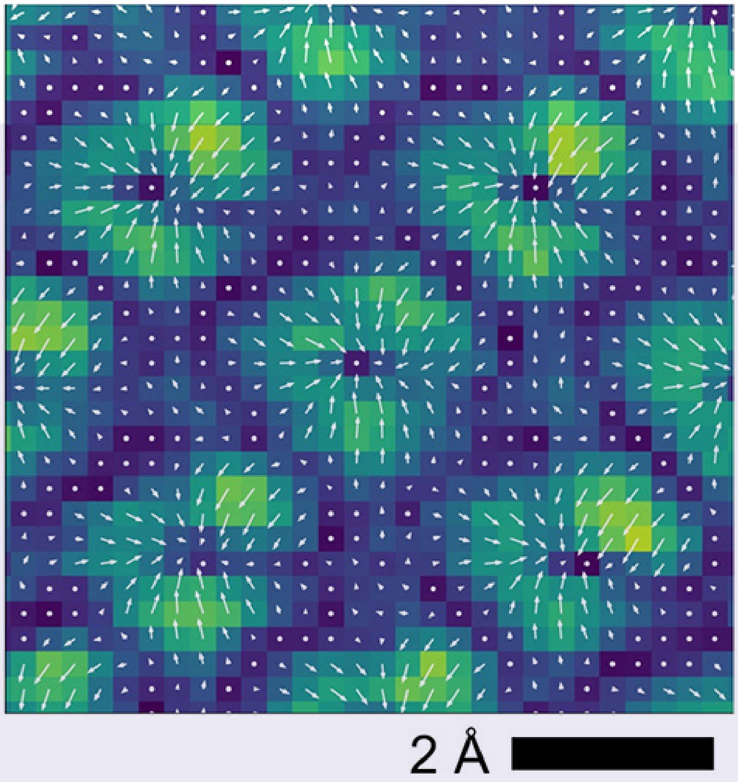
The good news is that there is a solution: Monolithic Active Pixel Sensors (MAPS) can be built Rad-Hard!



Electron microscopists have had success collecting 4D STEM data with radiation-hardened MAPS detectors, with 3-6 year sensor lifetimes.

If a MAPS detector's sensor is showing signs of radiation damage, replacing it is not a big deal. We built the sensors of all DE cameras to be removable so they can be easily replaced within a day!

For an example of 4D STEM on a Celeritas XS MAPS detector, see this recent publication* on orientation mapping of liquid crystals from Paul Voyles's group at the University of Wisconsin-Madison.



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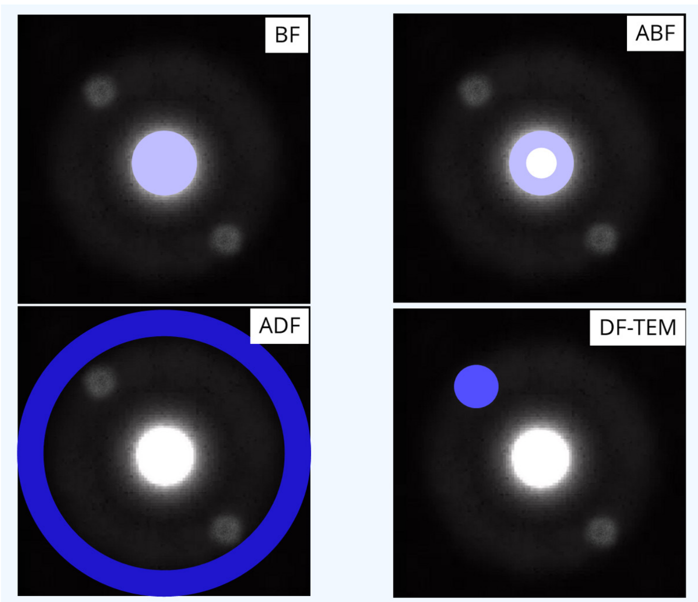
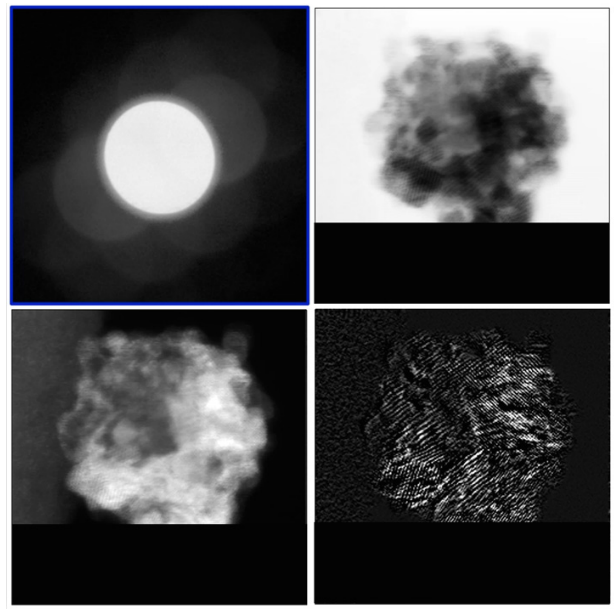
ISSUE #4: ANALYSIS SOFTWARE CAN BE DIFFICULT TO USE FOR BEGINNERS

As a 4D STEM cutting-edge technique, researchers may find that there is a lack of easy-to-use graphical interface software that allows beginners to analyze their 4D STEM data post-acquisition. Everyone hopes there to be some easy-to-use graphical analysis software that will automatically do all the analysis work for them. But for a relatively new technique, such as 4D STEM, researchers may find that they are among the first in the world to apply the technique to their material of interest, meaning that their analysis will need to follow a unique workflow that no software has been designed to handle before.

Because working in 4D STEM means you are working at the cutting-edge of electron microscopy, analyzing 4D STEM data typically requires knowledge of coding in Python or another programming language so that you can design appropriate analysis codes to get the best results.





There are Python-based open source software packages available for 4D STEM data analysis, including LiberTEM, Pyxem, and Py4DSTEM. Each of these software packages has a sizable user base, and worked examples published online (e.g. LiberTEM examples). Some offer tutorials to help beginners get started (e.g. Py4DSTEM tutorial), and others hold workshops to train new users (e.g. Hyperspy / Pyxem Workshop). Learning to use these open-source codes is worthwhile, because they offer enormous flexibility in terms of the types of analysis that can be applied to the data. This flexibility is something a commercial solution is unlikely to be able to match.

We know that scientists don't always want to become software developers, so Direct Electron's applications scientists offer training and support to help our customers get started with some analysis codes, for example generating electric field maps from 4D STEM datasets. That said, learning to work with the open source software is ultimately a good thing and gives scientists vastly more flexibility and control over their analysis!

These solutions to four common issues can help you to master the technically challenging technique of 4D STEM. We hope you find these tips helpful for your research and invite you to learn more in our learning center at https://directelectron.com/learning-center/, or by reaching out to us directly at https://directelectron.com/general-inquiries/.