Ultra-fast 4D STEM with real-time virtual image generation

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Direct Electron
INNOVATION PROPELLING DISCOVERY

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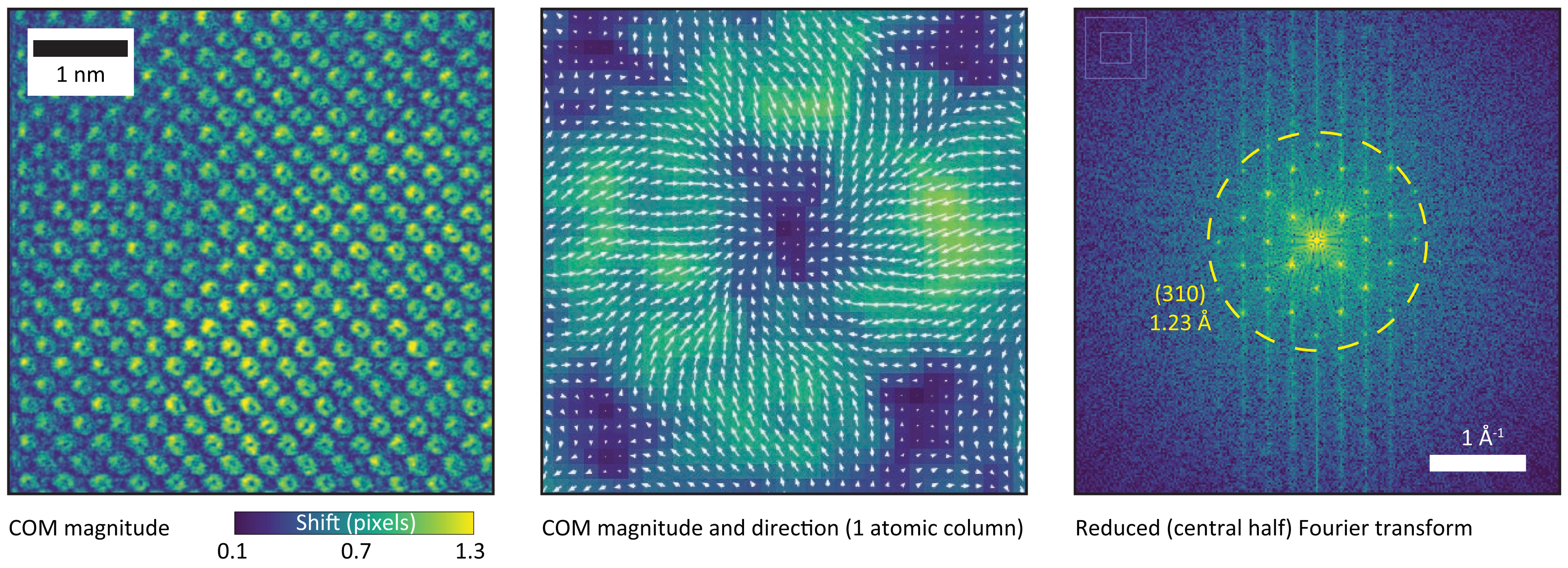
Celeritas XS for ultra-fast & flexible 4D-STEM

The Celeritas XS camera has a gapless 1024 × 1024 pixel area, optimized for 200 and 300 keV electron detection (sensitive down to 60 keV). The full-frame readout speed is 1960 frames per second (fps), and subarray readout enables up to 87,000 fps. The sensor can operate in global shutter readout mode to precisely synchronize the moving STEM probe with each frame acquired on the sensor. It's speed, size, and features make it ideal for a wide-range of STEM and TEM experiments.



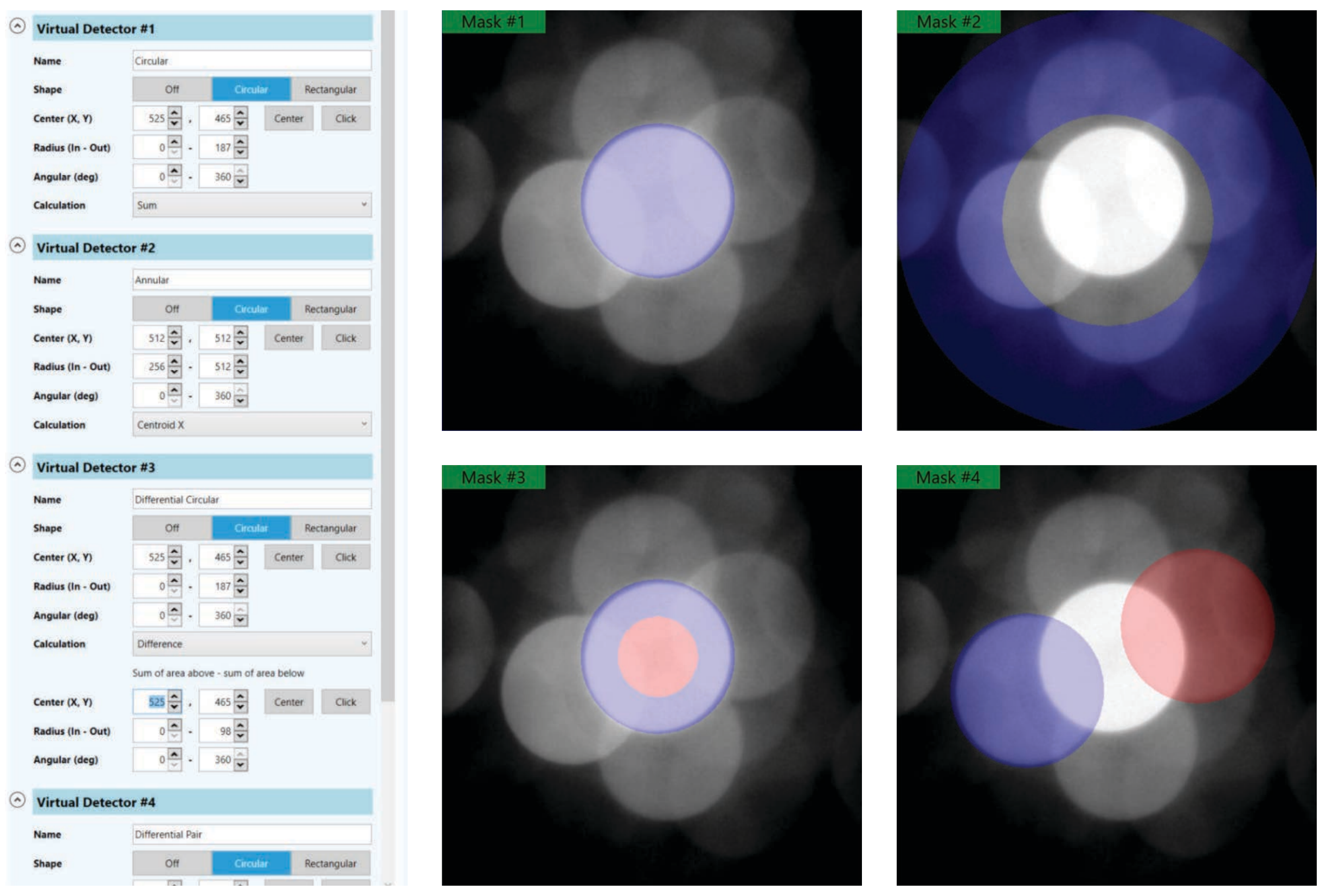
COM magnitude

COM magnitude and direction (1 atomic column)

Reduced (central half) Fourier transform

Figure 1: 4D STEM center-of-mass (COM) reconstruction of strontium titanate with 512 × 512 specimen pixels, acquired with the Celeritas XS camera in only 3.04 seconds. The Celeritas XS camera was operating at 86 kHz (11.6 µs dwell time) with a readout area of 256 × 64 detector pixels. Data acquired by Jingrui Wei from the group of Paul Voyles (University of Wisconsin-Madison, Madison, WI USA).

Data acquisition workflow with real-time feedback



Virtual Detector #1

Name	Circular
Shape	Off [✓ Circular] Rectangular
Center (X, Y)	525 , 465
Radius (In - Out)	0 - 187
Angular (deg)	0 - 360
Calculation	Sum

Virtual Detector #2

Name	Annular
Shape	Off [✓ Circular] Rectangular
Center (X, Y)	512 , 512
Radius (In - Out)	256 - 512
Angular (deg)	0 - 360
Calculation	Centroid X

Virtual Detector #3

Name	Differential Circular
Shape	Off [✓ Circular] Rectangular
Center (X, Y)	525 , 465
Radius (In - Out)	0 - 187
Angular (deg)	0 - 360
Calculation	Difference

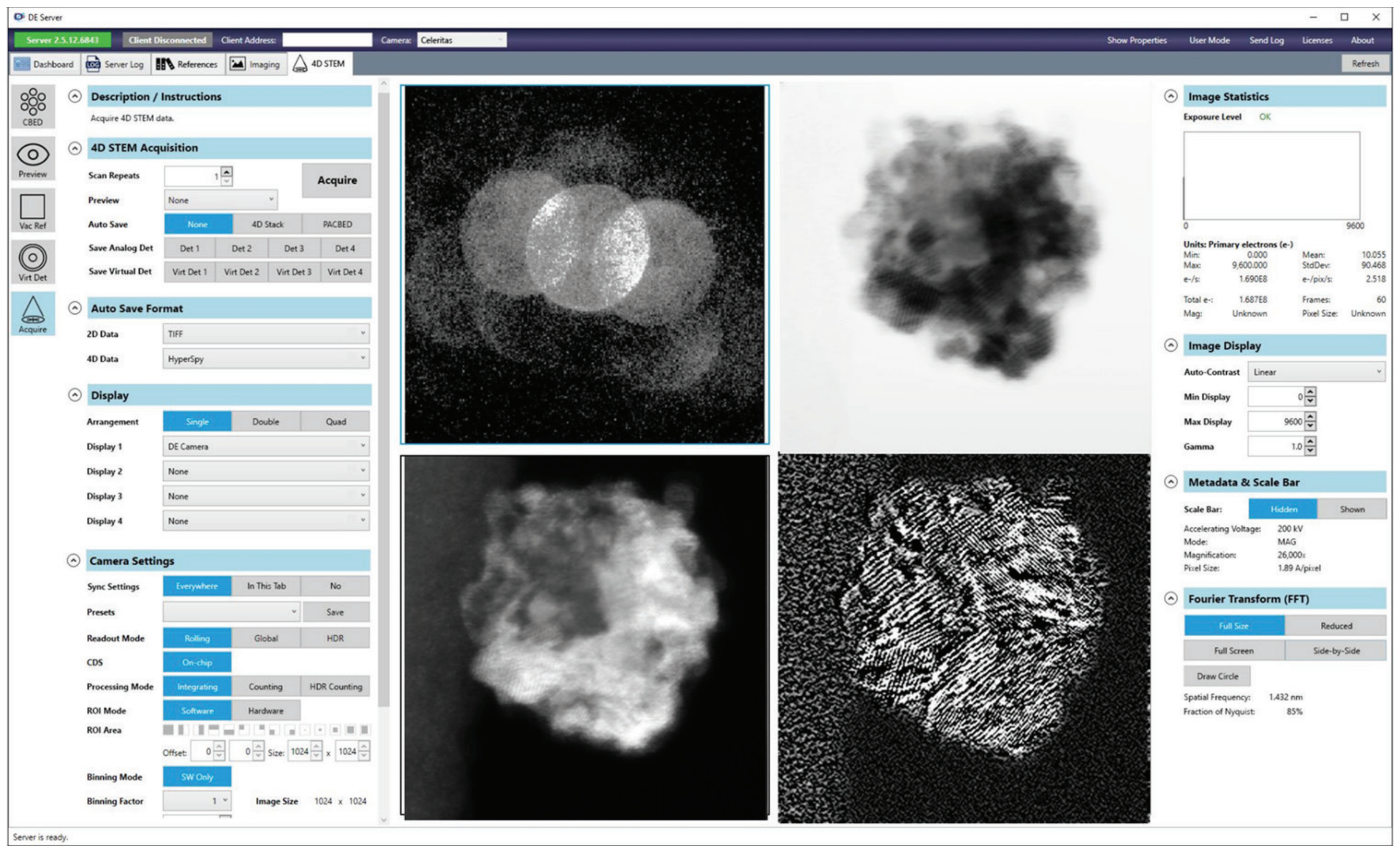
Sum of area above - sum of area below

Center (X, Y)	525 , 465
Radius (In - Out)	0 - 98
Angular (deg)	0 - 360

Virtual Detector #4

Name	Differential Pair
Shape	Off [✓ Circular] Rectangular

Figure 2: The "Dimension" module for the DE-MissionControl (DE-MC) enables flexible 4D STEM acquisition with real-time virtual image generation. **(Left)** The user can define up to four virtual image masks. Masks be used to calculate the sum, difference (red vs blue masks), center-of-mass, or standard deviation of regions of each frame. **(Below)** During 4D STEM acquisition, the user can view the real-time camera display as well as the virtual images being generated during the experiment. Data is also streamed to disk. (Note: The masks shown at left do not correspond to the acquisition below.)



Description / Instructions

Acquire 4D STEM data.

4D STEM Acquisition

Scan Repeats	1
Preview	None
Auto Save	[✓ None] 4D Stack PACBED
Save Analog Det	Det 1 Det 2 Det 3 Det 4
Save Virtual Det	Virt Det 1 Virt Det 2 Virt Det 3 Virt Det 4

Acquire

Auto Save Format

2D Data	TIFF
4D Data	HyperSpy

Display

Arrangement	[✓ Single] Double Quad
Display 1	DE Camera
Display 2	None
Display 3	None
Display 4	None

Camera Settings

Sync Settings	[✓ Everywhere] In This Tab No
Presets	Save
Readout Mode	[✓ Rolling] Global HDR
CDS	[✓ On-chip]
Processing Mode	[✓ Integrating] Counting HDR Counting
ROI Mode	[✓ Software] Hardware
ROI Area	Offset: 0 0 Size: 1024 x 1024
Binning Mode	[✓ SW Only]
Binning Factor	1

Image Size 1024 x 1024

Image Statistics

Exposure Level OK

0 9600

Units: Primary electrons (e-)

Min:	0.000	Mean:	10.055
Max:	9,600.000	StdDev:	90.468
e-/s:	1.690E8	e-/pix/s:	2.518
Total e-:	1.687E8	Frames:	60
Mag:	Unknown	Pixel Size:	Unknown

Image Display

Auto-Contrast	Linear
Min Display	0
Max Display	9600
Gamma	1.0

Metadata & Scale Bar

Scale Bar:	[✓ Hidden] Shown
Accelerating Voltage:	200 kV
Mode:	MAG
Magnification:	26,000x
Pixel Size:	1.89 A/pixel

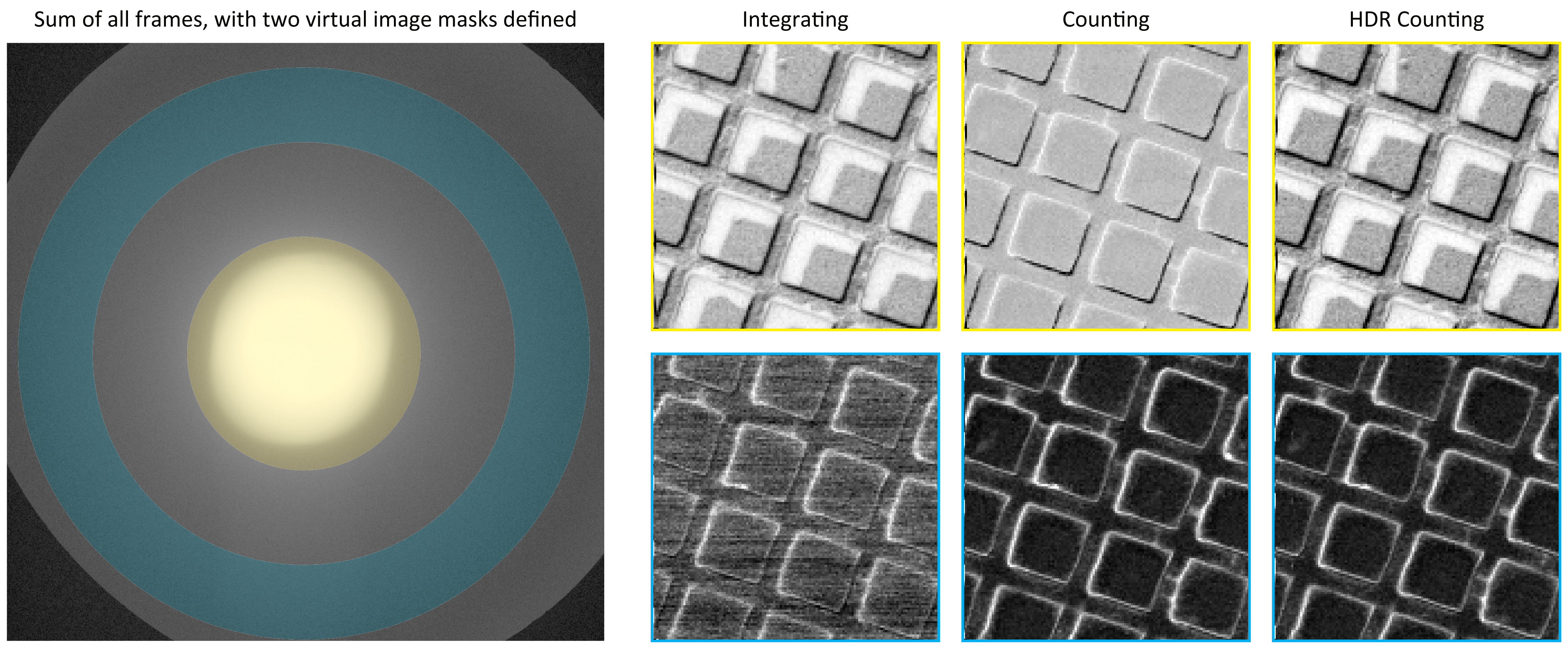
Fourier Transform (FFT)

[✓ Full Size] Reduced
Full Screen Side-by-Side
Draw Circle

Spatial Frequency:	1.432 nm
Fraction of Nyquist:	85%

Server is ready.

Maximizing data quality with "HDR Counting"



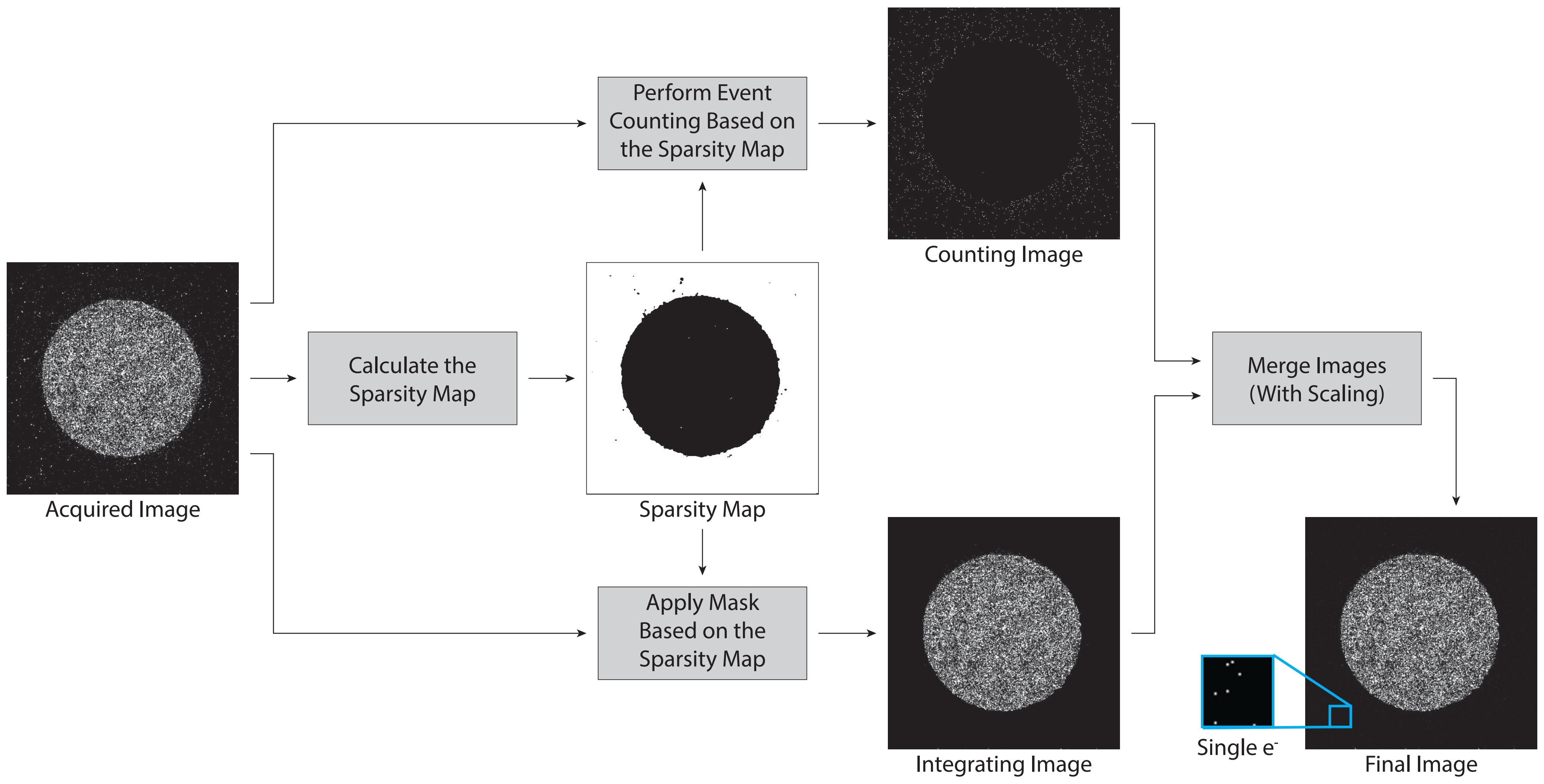
Sum of all frames, with two virtual image masks defined

Integrating

Counting

HDR Counting

Figure 3: Demonstration of HDR Counting for 4D STEM acquisition of a line-grating calibration grid. At the left is the sum of all frames from the HDR Counting data set, with two virtual image masks overlaid on the image: a bright-field (BF) virtual detector shown in yellow and a dark-field (DF) virtual detector shown in blue. Keeping the beam intensity, scanning parameters, and specimen area the same, we acquired 4D STEM datasets with the camera operating in integrating (linear) mode, counting mode, and HDR Counting mode. The resulting virtual images (generated in real-time during data acquisition) are shown on the right. Because the BF disk is too bright for electron counting, the BF virtual image shows the best contrast and detail in integrating mode. Because the DF area is sparse, the DF virtual image shows the best contrast and lowest noise in counting mode. HDR Counting mode automatically combines the best performance of integrating and counting mode, to generate optimum images for both BF and DF virtual images simultaneously.



Acquired Image

Calculate the Sparsity Map

Sparsity Map

Perform Event Counting Based on the Sparsity Map

Counting Image

Apply Mask Based on the Sparsity Map

Integrating Image

Merge Images (With Scaling)

Single e⁻

Final Image

Figure 4: Description of the patented (US Patent # 11,252,339) HDR Counting algorithm. Each dark-corrected frame from the camera is processed to calculate a sparsity map for that particular frame. The sparsity map is calculated by finding the number of unilluminated pixels (less than the counting threshold) within a neighborhood around each pixel in the frame. Assuming that electrons are uniformly distributed over the area of each neighborhood, the fraction of unilluminated pixels within a neighborhood correlates to the sparsity of events on the sensor. We establish a sparsity threshold to distinguish between bright and sparse neighborhoods. Pixels with sparse neighborhoods are processed with electron counting, while pixels with bright neighborhoods are not. The two resulting images are then scaled (based on the ADU/electron for the sensor at the experiment's accelerating voltage) and merged to generate the HDR Counting output frame.

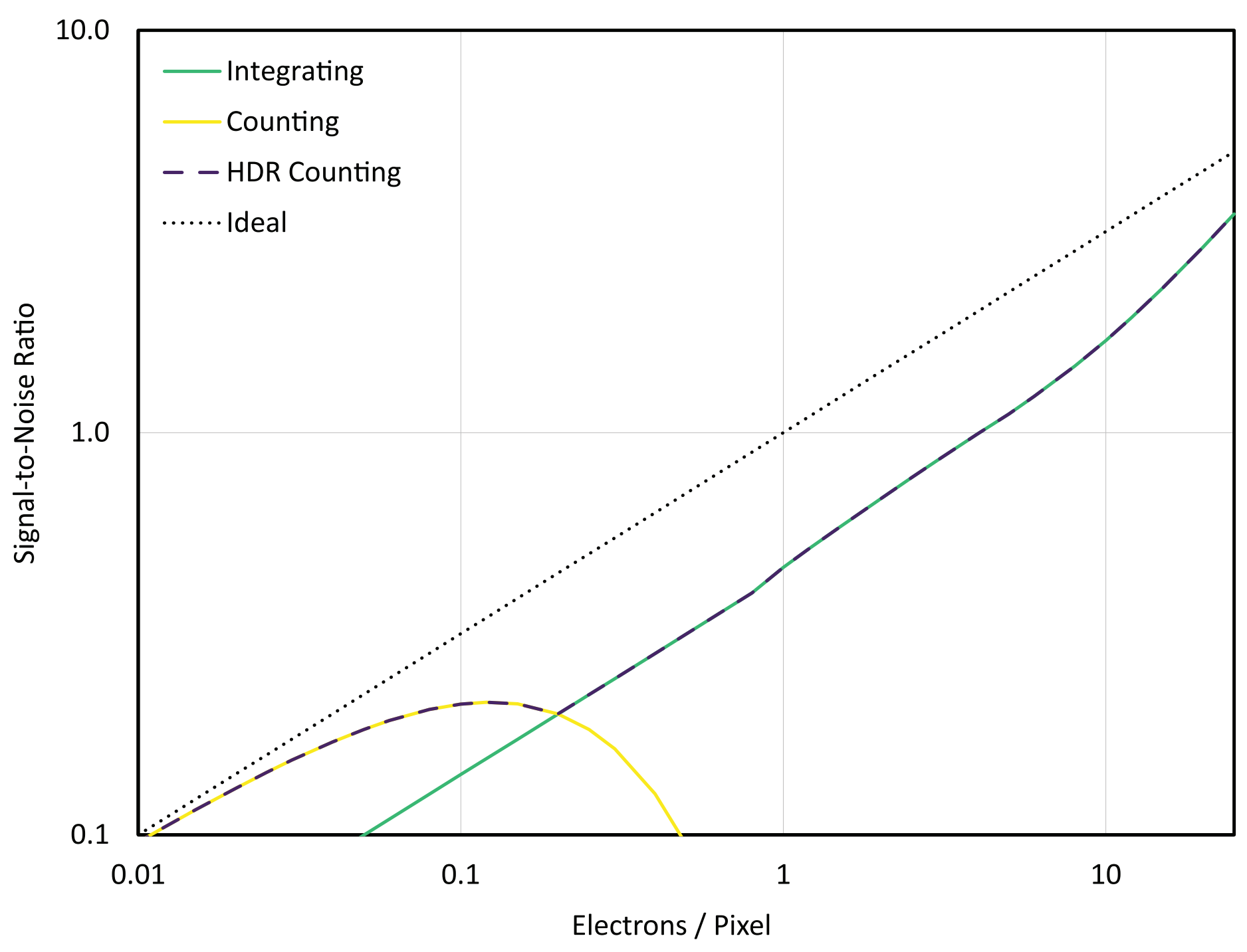


Figure 5: Simulated signal-to-noise ratio (SNR) based on Poisson statistics, detective quantum efficiency (DQE), and coincidence loss for integrating, counting, and HDR Counting on the Celeritas XS camera. For sparse illumination (e.g., in the DF area), electron counting improves SNR by ~2× compared to integrating. However, as the illumination increases, coincidence loss (multiple electrons hitting the same or adjacent pixels within the same frame) begins to attenuate the SNR of counting. At ~0.2 e-/pixel on Celeritas, coincidence loss has reduced the SNR of counting to match that of integrating. HDR Counting automatically selects counting or integrating for each pixel depending on the local illumination, thereby maximizes SNR across a broad range of intensities.

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