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A New Fast Helium Ion Imaging Technique Through Rapid Acquiring and Restoring Using the Point Spread Function Deconvolution Method

Pouya Tavousi[1], Bahar Ahmadi[2], Nicholas May[2], Sunshine Snider-Drysdale[2], Zahra Shahbazi[3], Daniel Di Mase[4] and Sina Shahbazmohamadi[2]

[1]Univeristy of Connecticut, Storrs, Connecticut, United States, [2]REFINE Lab, University of Connecticut, Storrs, Connecticut, United States, [3]Manhattan College, Riverdale, New York, United States, [4]Aerocyonics Inc, East Greenwich, Rhode Island, United States

Introduction: Scanning helium ion microscopy (HIM) offers a superior resolution (up to 0.5nm) and depth of field (up to 5X more) compared to scanning electron microscopy (SEM) thanks to high source brightness, low energy spread, and small diffraction effects [10]. HIM also can accommodate non-conductive samples without the use of conductive coatings. Compared to other Ion beams, it has less ion damage during imaging due to the light mass of the helium ions. However, one of the drawbacks of HIM is its speed. On average, HIM is 5 times slower than SEM which can be a deterring factor when larger areas need to be imaged. In this study, we explore the use of point spread function (PSF) deconvolution method as a means to speed up HIM imaging process. PSF deconvolution has successfully been used to restore SEM images but its effectivity on Ion-based imaging is less explored. Here we have studied whether faster HIM imaging using shorter dwell times can be restored by PSF deconvolution. We have also assessed the quality of images using quantitative methods.

Experiment Design: The sample we are using through this study is an SEM calibration sample which consists of nanoparticles in the range of 30-300 nm. We first image the exact same location of the sample with different dwell times ([0.1,0.2,0.5,1,2,5,20] microsecond). Since the smallest particle size is 30 nm, we assume that the pixel size of 15 nm will provide us with sufficient information. For the sake of comparison, we will also image the sample with the pixel size of 5nm and 3 nm, keeping the dwell times the same. Then we restore the images using the PSF measurement and deconvolution method in Aura Workstation developed by Nanojehm company [11]. Finally, we assess the quality of the restored images.

Imaging and Restoration Method: Before any image processing steps could be executed, images from the Nanojehm calibration sample and the true sample needed to be taken. The Nanojehm calibration sample is composed of gold nanoparticles 18.2nm in size on carbon film secured on a metal stub by copper tape. The calibration sample is comprised of gold nanoparticles on a carbon substrate that is 6mm in diameter and 2mm in height and offers 30-300nm particles. Aura workstation is used to process the images once they are taken. Aura takes an uploaded calibration image at the desired pixel size, with as many individual gold nanoparticles shown as possible. It calculates an average nanoparticle size called a "stacked particle" and then calculates the PSF of the beam from that average. The PSF is traditionally the "spatial distribution of the electron beam's current density" but since the microscope, in this case, is a HIM, it will be the current density of the helium ion beam [1].

Image Quality Assessment (IQA) Method: There are many works available in the literature studying different IQA methods [2-5]. Generally, the methods can be categorized into two subcategories: full-reference-based IQA where images are compared with a high-quality image, and non-reference-based IQA (or blind IQA), which tries to evaluate perceptual quality of natural visual images similar to human rating. Here, we assume that the restored images taken by 20 microsecond dwell time are the reference

images we can use for quality assessment. We assess the images taken by different dwell time by several traditional methods such as “the peak signal to noise ratio (PSNR)” and “the structural similarity index (SSIM)”, and some novel methods like “the feature similarity index (FSIM)”[6], “the multi-scale structural similarity scale (MS-SSIM)” [7], and “the visual information fidelity (VIF)” [8]. There are some challenges associated with these methods [9], hence we are also working on developing a more practical approach, where an automated workflow can segment and label the particles in each image and calculate the error in segmentation.

Results and Conclusion: The sample was imaged at different pixel sizes and different dwell times, Fig1.a shows the registered area within the field of view of 30 micrometers (the red image), 10 micrometers (the cyan image), and 6 micrometers (the gray image). Each field of view was imaged with different dwell time (ranging from 0.1 microseconds to 20 microseconds), and restored by the PSF deconvolution method at Aura workstation. Fig1.b shows an observed image, the stacked particles for measuring the PSF, and the restored image. Fig 1.c shows two pairs of images taken at 3 nm pixel size. The pair on the left shows observed and restored images taken at 0.1 microseconds dwell time, and the pair on the right shows observed and restored images taken at 5 microseconds. Similar to Fig1.c, Fig1.d and Fig1.e show pairs of images taken at the same dwell time by the pixel size 5nm, and 15 nm respectively. For the sake of comparison, these images have been registered, up-sampled and cropped to match the exact same location of the images taken at 3nm pixel size. Fig.2 shows some of the results of the IQA methods. Images on Fig2.a are taken at a pixel size of 15nm, the before and after deconvolution images have been shown for different dwell time. Fig2.b is a table displayed the peak signal to noise ratio value of each observed and restored image comparing to the restored image taken by 20 dwell time. The amount of improvement explains this technique’s performance. A good improvement is shown on images that were taken at a faster rate, which introduce more noise was to the image. Another useful IQA method is VIF which evaluates the quality of an image comparing to its reference. Fig2.c shows calculated VIF value for each restored image, and measure the similarity of each image to the restored image taken at 20 microsecond dwell time, some sample images are shown in Fig2. d. These improvements and enhancement prove the effectiveness of the PSF deconvolution method for helium ion microscopy and enable a fast solution for helium ion imaging.

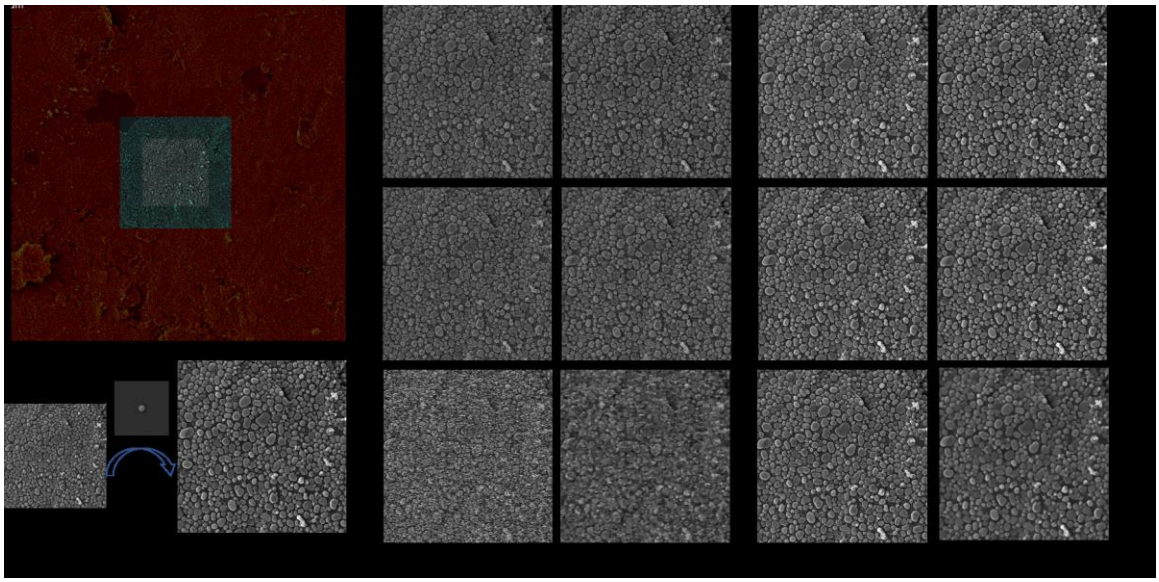

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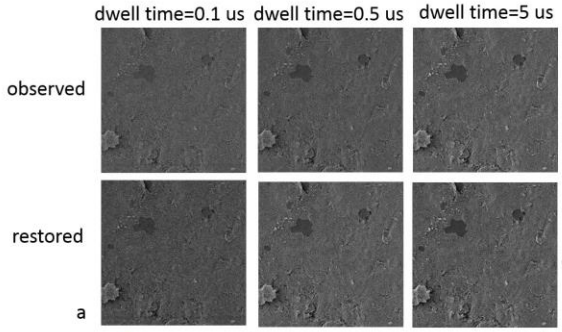
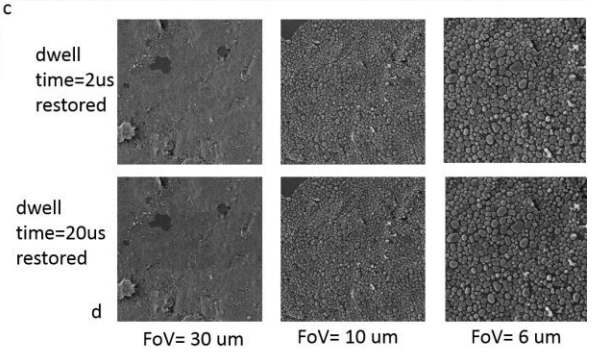
Figure 1. a)The image of the calibration sample taken at 3 different fields of view (FoV=30 micrometer: Red image, FoV=10 micrometer: Cyan image, FoV=6 micrometer: Gray image); b) The PSF deconvolution on one of the images (FoV=6 micrometer, dwell time=20microseconds) the original image, the stacked particles, and the restored image; c)observed and restored images of 3nanometers pixel size, from left, the observed image taken with dwell time of 0.1 microseconds and its restored image, the observed image taken with dwell time of 5 microseconds and its restored image; d) The observed and restored images taken at 5 nanometers pixel size, the left is taken at 0.1 microseconds dwell time and the right one taken at 5 microseconds dwell time; e) the observed and restored images taken at 15 nanometers pixel size, the left is taken at 0.1 microseconds dwell time and the right one taken at 5 microseconds. For the sake of comparison, the images at Fig1.d and Fig1. e have been registered and cropped to match the same area as Fig1.c



Dwell time (microsecond)	FoV= 30 micrometer		FoV= 10 micrometer		FoV=6 micrometer	
	Speed	VIF value	Speed	VIF value	Speed	VIF value
0.1	200X	0.238754255	200/9X	0.02844908	8X	0.01963887
0.2	100X	0.192803093	100/9X	0.09053475	4X	0.09750878
0.5	40X	0.341905152	40/9X	0.16588161	40/25X	0.05285207
1	20X	0.377502793	20/9X	0.14700995	20/25X	0.15728918
2	10X	0.405698	10/9X	0.19216747	10/25X	0.17909328
5	4X	0.421771082	4/9X	0.2206144	4/25X	0.26980963
20	X	1	X/9	1	X/25	1

c



Dwell time (microsecond)	FoV= 30 micrometer		
	PSNR Observed	PSNR Restored	improvement (%)
0.1	33.048031	56.64323	71.39668857
0.2	37.431888	53.4243	42.72403933
0.5	45.499869	53.81817	18.28203903
1	46.558428	55.88329	20.0282995
2	51.274876	51.72654	0.88086365
5	52.592279	59.54043	13.21135182
20	55.493404	inf	_

b

Figure 2. a) The before and after deconvolution images taken by 15 nanometers pixel size and different dwell time; b) a table of the peak signal to noise ratio value of each observed and restored image having the restored image, taken by 20 microseconds dwell time as the reference; c) the imaging speed and the VIF value having the restored image taken at 20 microsecond dwell time as the reference for each restored image; d) The restored images of 2 microseconds dwell time and 20 microseconds dwell time at different fields of view.

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