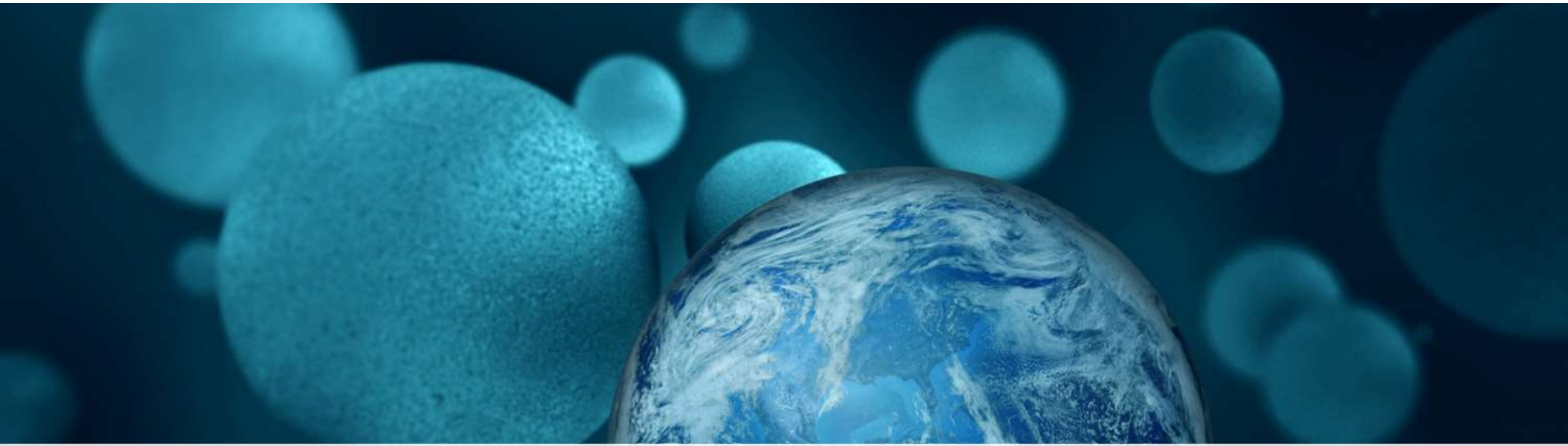

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Machine Learning for SEM Image Enhancement

Umesh Adiga
01/14/2022

Highly Confidential

Why this proposal

- Customer complaints about image quality

Poor Image Quality

1. Image appearance or visual quality (example: poor SNR, CNR, uniformity, resolution, etc.)

   Better visual quality to help marketing/sales and add psychological perception that our machines are performing better. May facilitate better metrology too.

2. Image information content (example: lack of material distinction in 3DNAND, etc.)

   Most important quality and this require combination of hardware and improved image reconstruction software

3. Amenability to precision metrology (example: inability to facilitate high throughput precision)

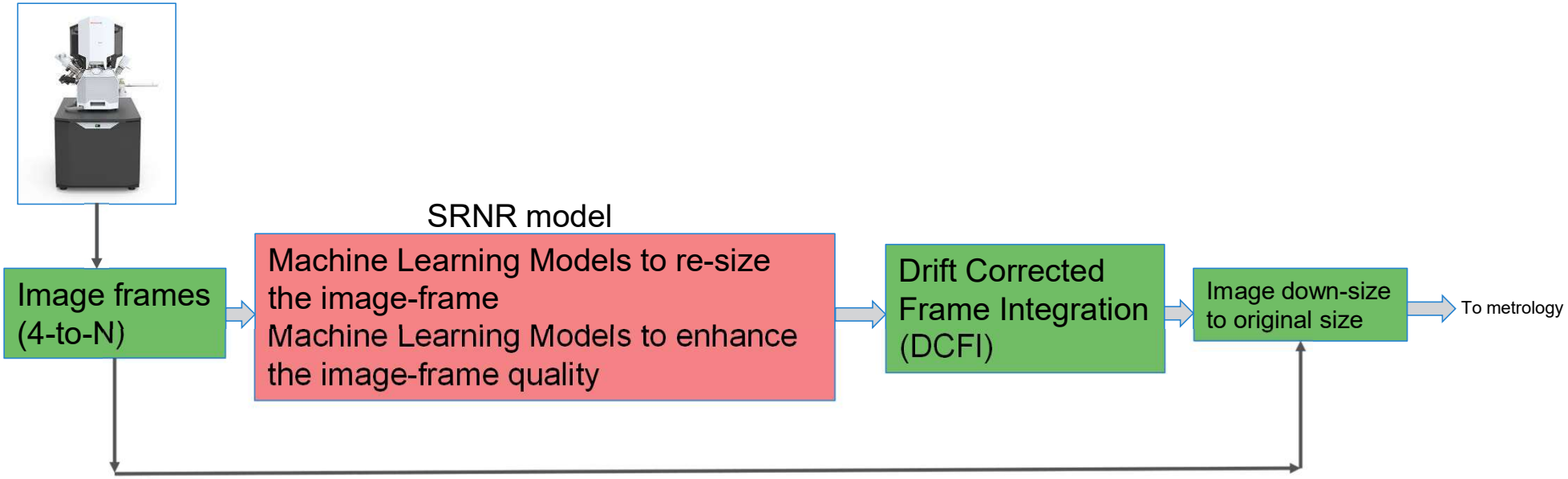
   More ambiguous. Depends on what you are measuring.

In this work we are dealing with the first topic, namely, "Image appearance or visual quality"

In general: Super Resolution Noise Reducer (SRNR) model

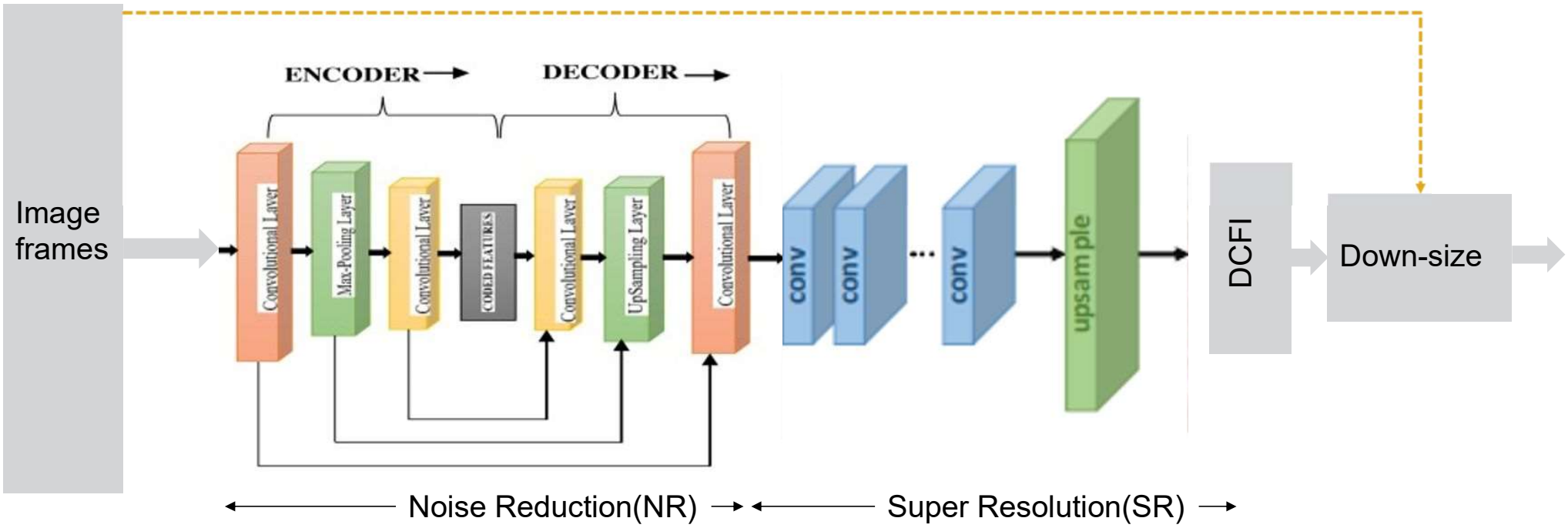
1. Up-size the image through machine learning methods (super resolution*) with minimum net-loss of information
2. Enhance image quality such as SNR, CNR, Uniformity, Gamma using dedicated machine learning models
3. Perform Drift Corrected Frame Integration (DCFI)
4. Down-size the image to original size

(down-sizing by a factor of 2 increases the SNR by a factor of $\sqrt{2}$)

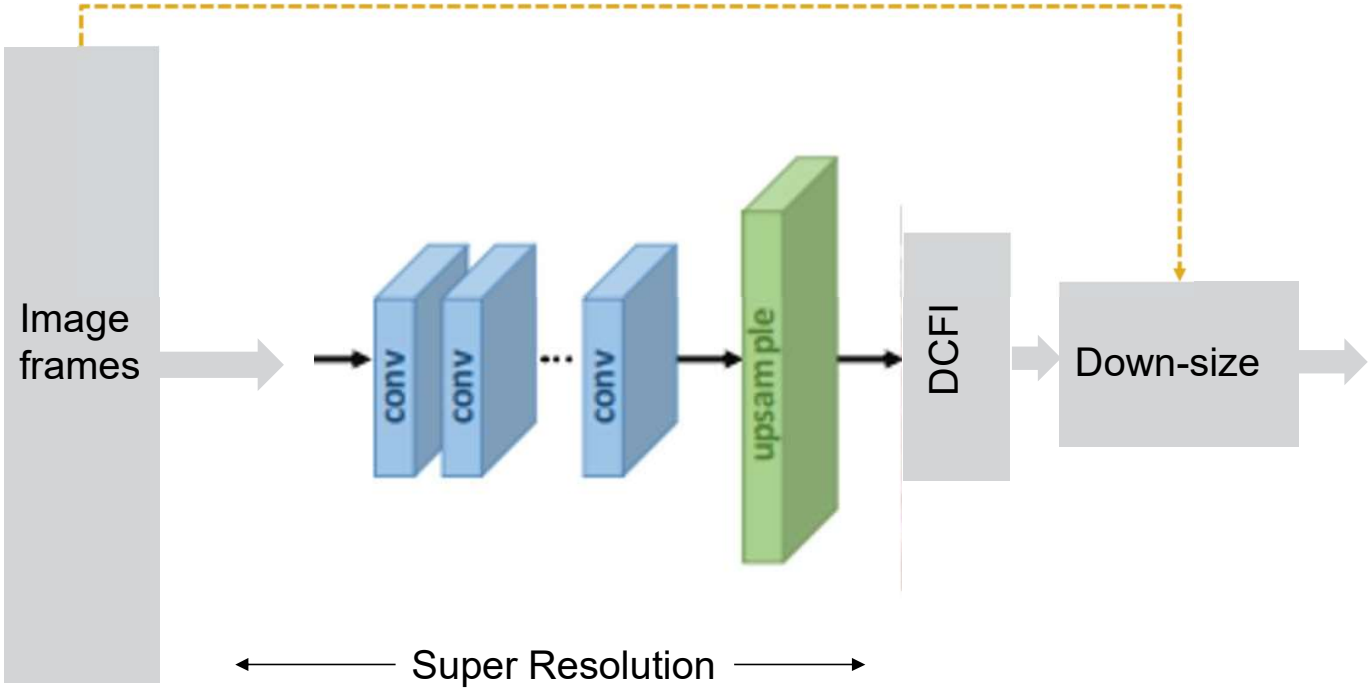


*Super resolution does not improve "resolution" of the original input image

Proposed Architecture for Neural Network: NRSR model



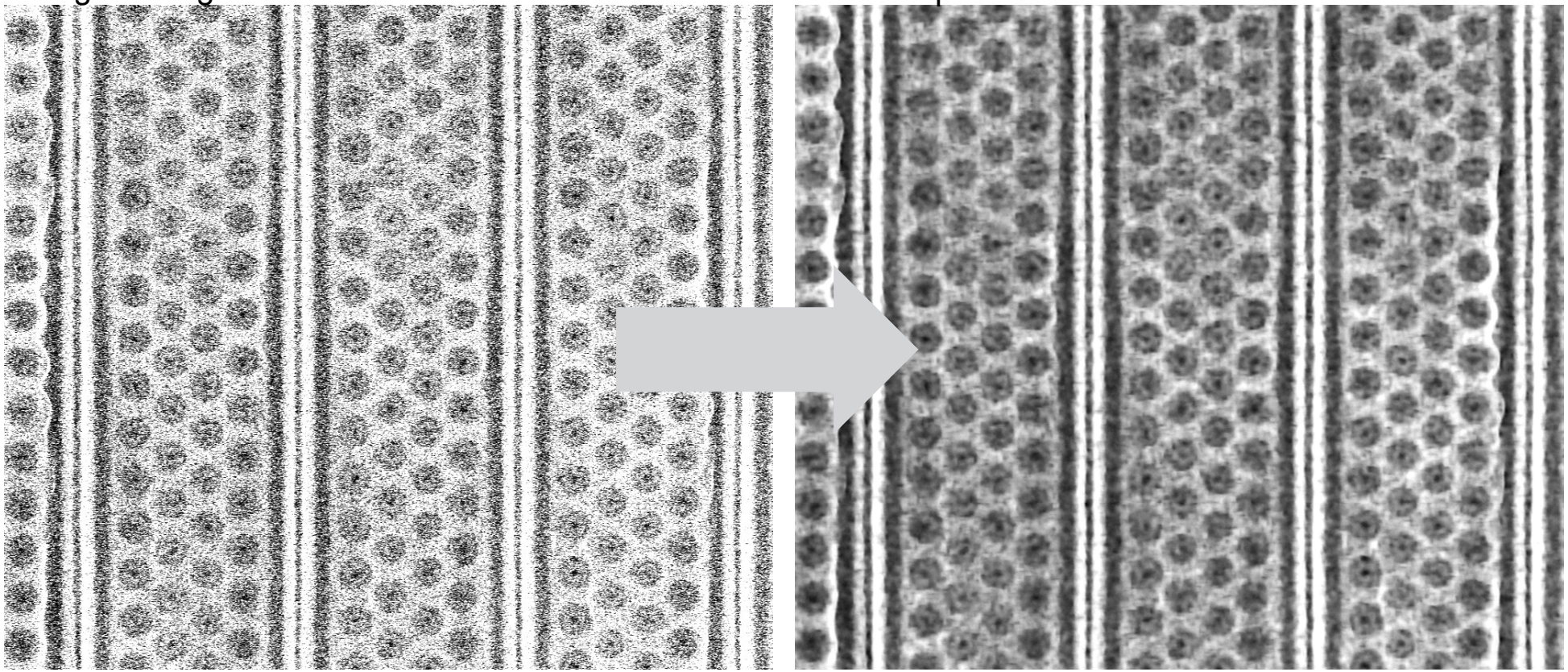
Super Resolution Model Architecture



Individual Image Frame Super Resolution (SR) model: 3D NAND (Verios SEM) trained

Original Single Frame

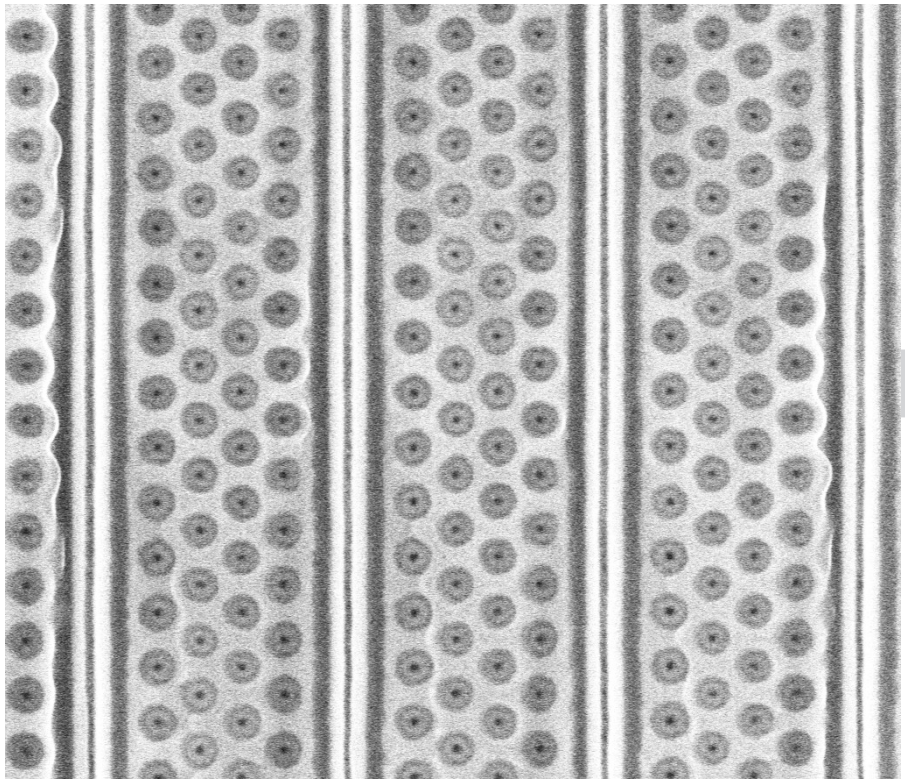
After super resolution enhancement



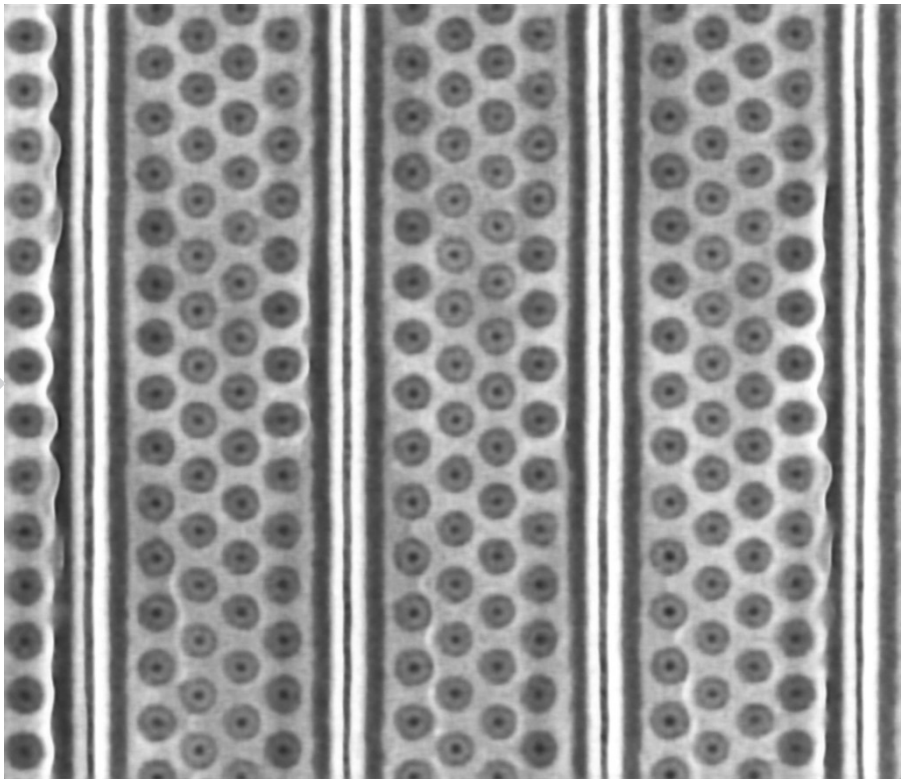
Multiple frames (of very low dwell time) are enhanced by SR model prior to DCFI

DCFI of image frames before and after SR model application:

Before



After

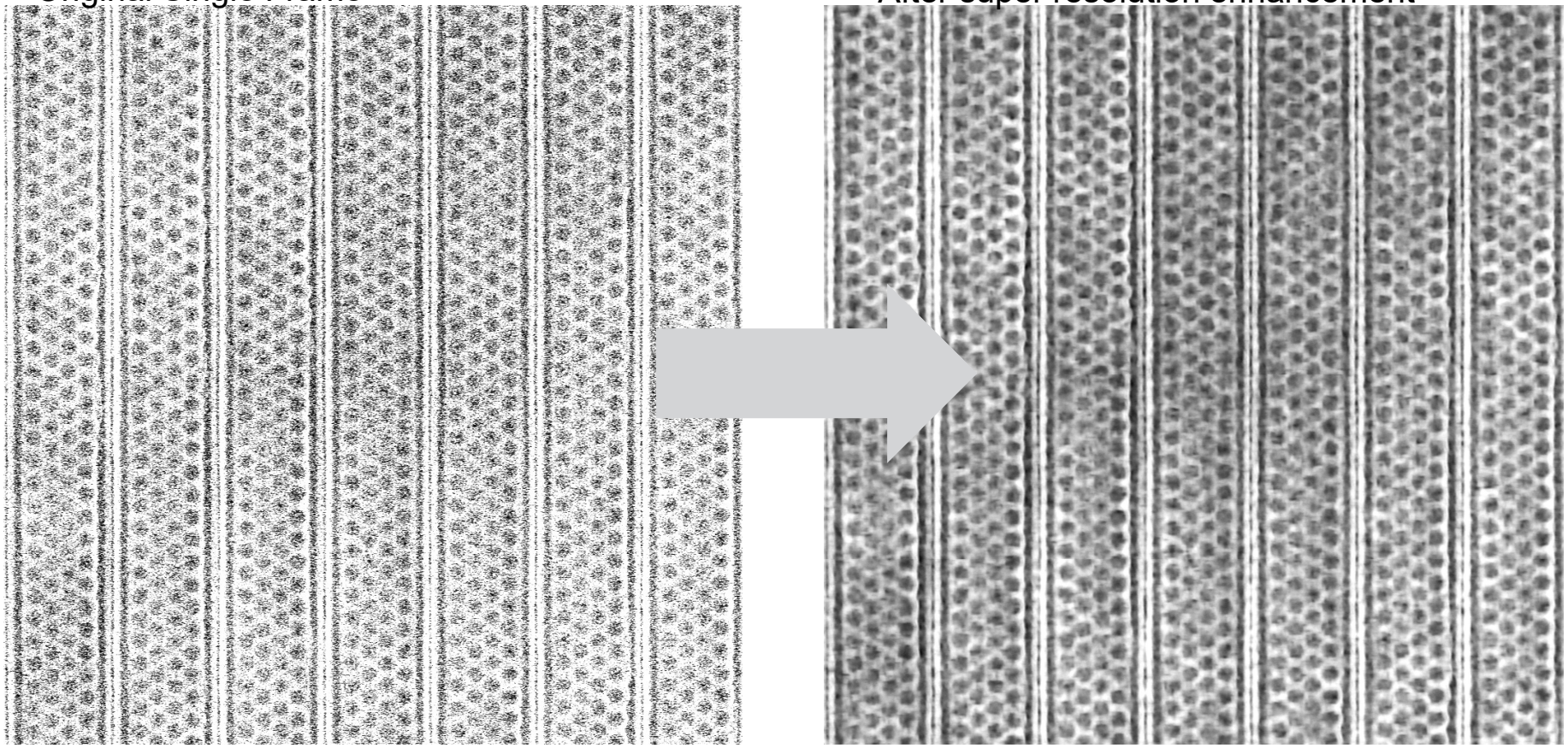


If you zoom 200%, you will see pixel level effect of super resolution

Individual Image Frame Super Resolution (SR) model: 3D NAND (Verios SEM) trained

Original Single Frame

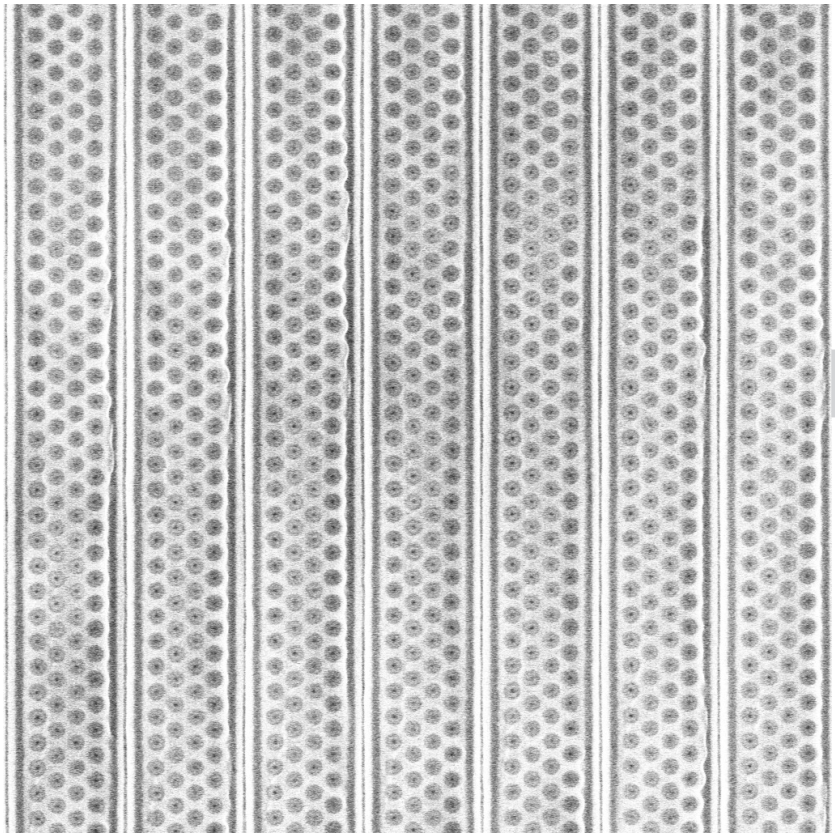
After super resolution enhancement



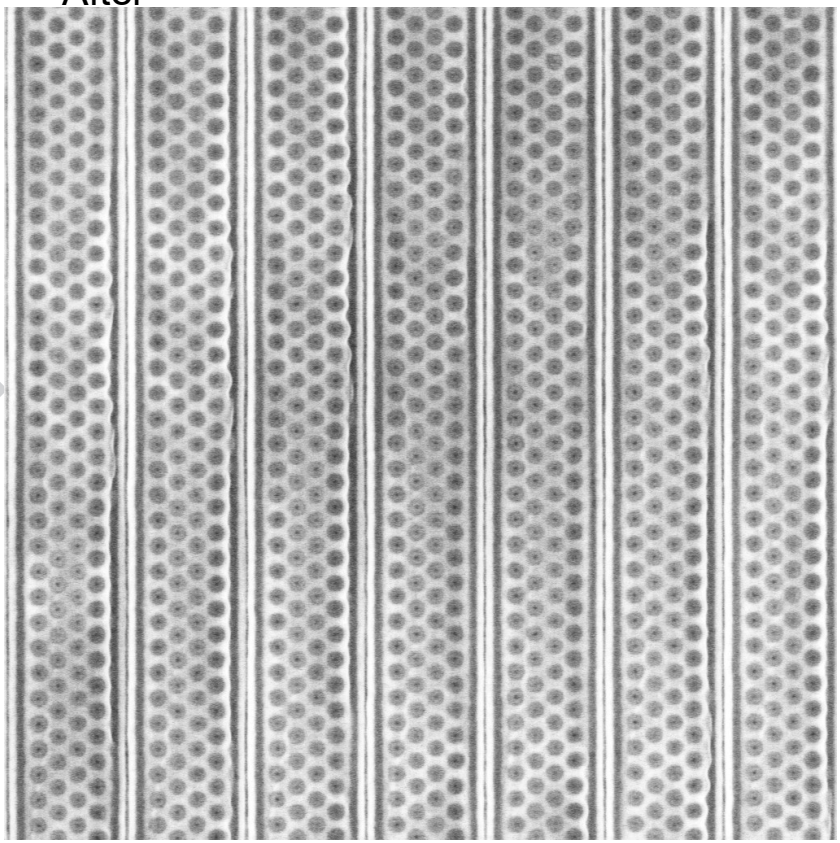
Multiple frames (of very low dwell time) are enhanced by SR model prior to DCFI

DCFI of image frames before and after SR model application:

Before



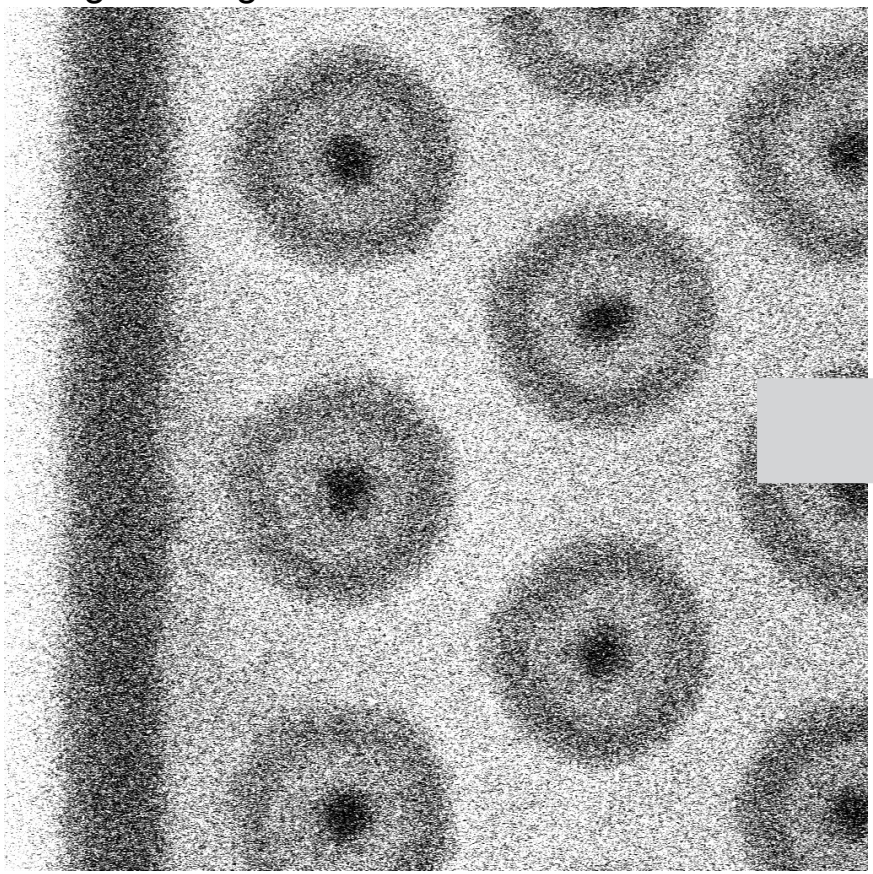
After



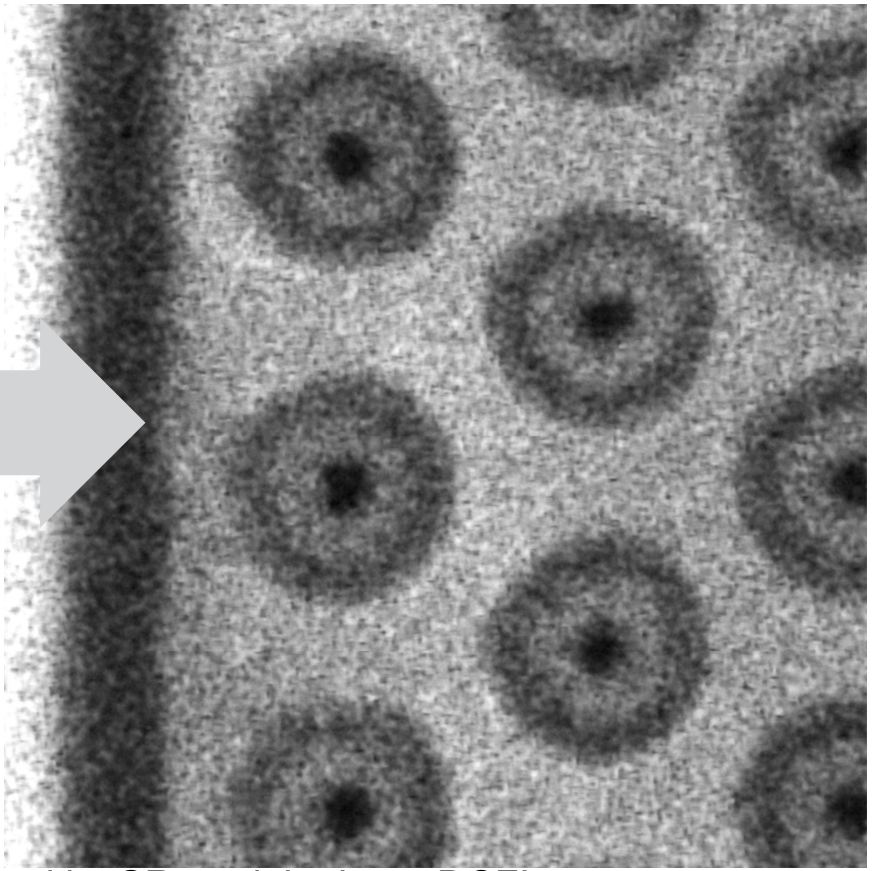
We will rework the SR training to reduce the amount of blur

Individual Image Frame Super Resolution (SR) model: 3D NAND (Verios SEM) trained

Original Single Frame



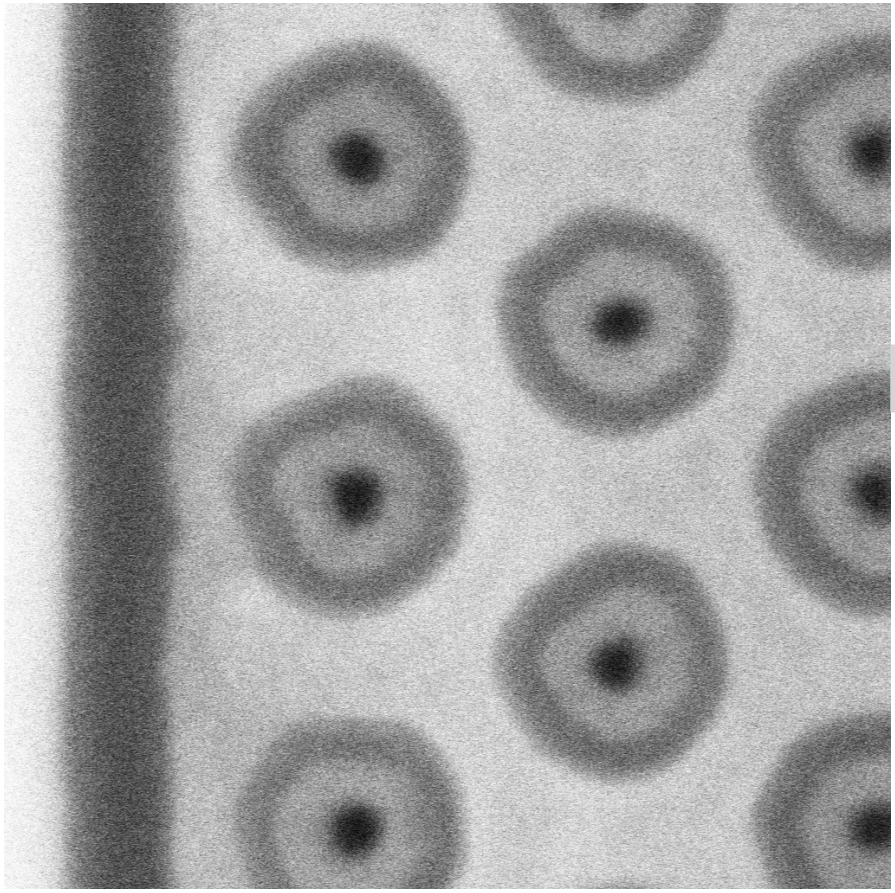
After super resolution enhancement



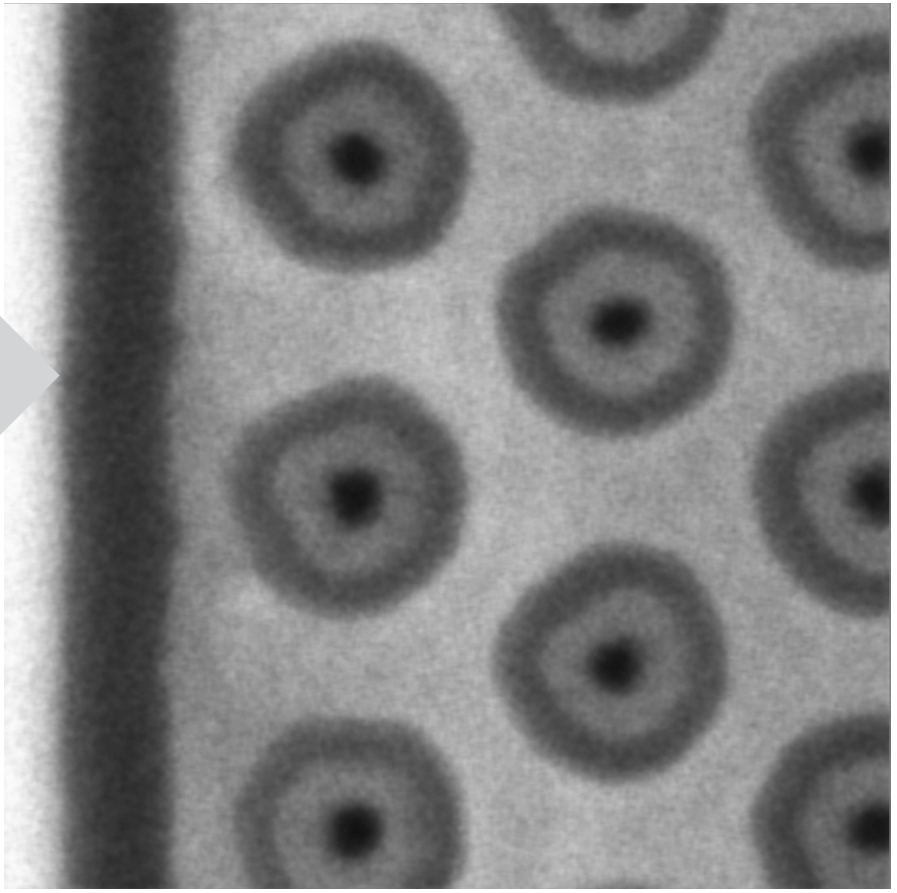
Multiple frames (of very low dwell time) are enhanced by SR model prior to DCFI

DCFI of image frames before and after SR model application:

Before



After



We will rework the SR training to reduce the amount of blur

Conclusion on SR model enhancement

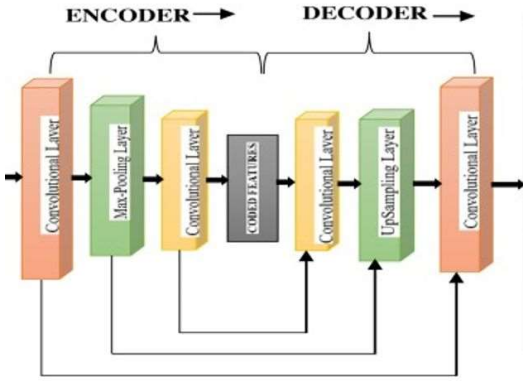
- Noise reduction in individual image frames is significant
- Super resolved image has 4X more pixel count and hence easier for metrology algorithm deployment
- Transition from one brightness level to another is smooth and somewhat sharp.
- Result images appear to be darker in overall brightness. Either the training data should be modified to enhance the image brightness or use a conventional post-processing algorithm to enhance the image brightness.
- Images appeared to be somewhat blurred. Retraining with sharp images might reduce this effect.

Proposal for Noise Reducer Model

2. For every image-frame, use auto-encoder decoder models to improve SNR, CNR, uniformity, gamma correction, etc.

Machine learning model here would consist of
1. Auto-encoders and
2. Auto-decoders

Accomplishes
1. Noise reduction,
2. Contrast and Brightness standardization and
3. Gama correction

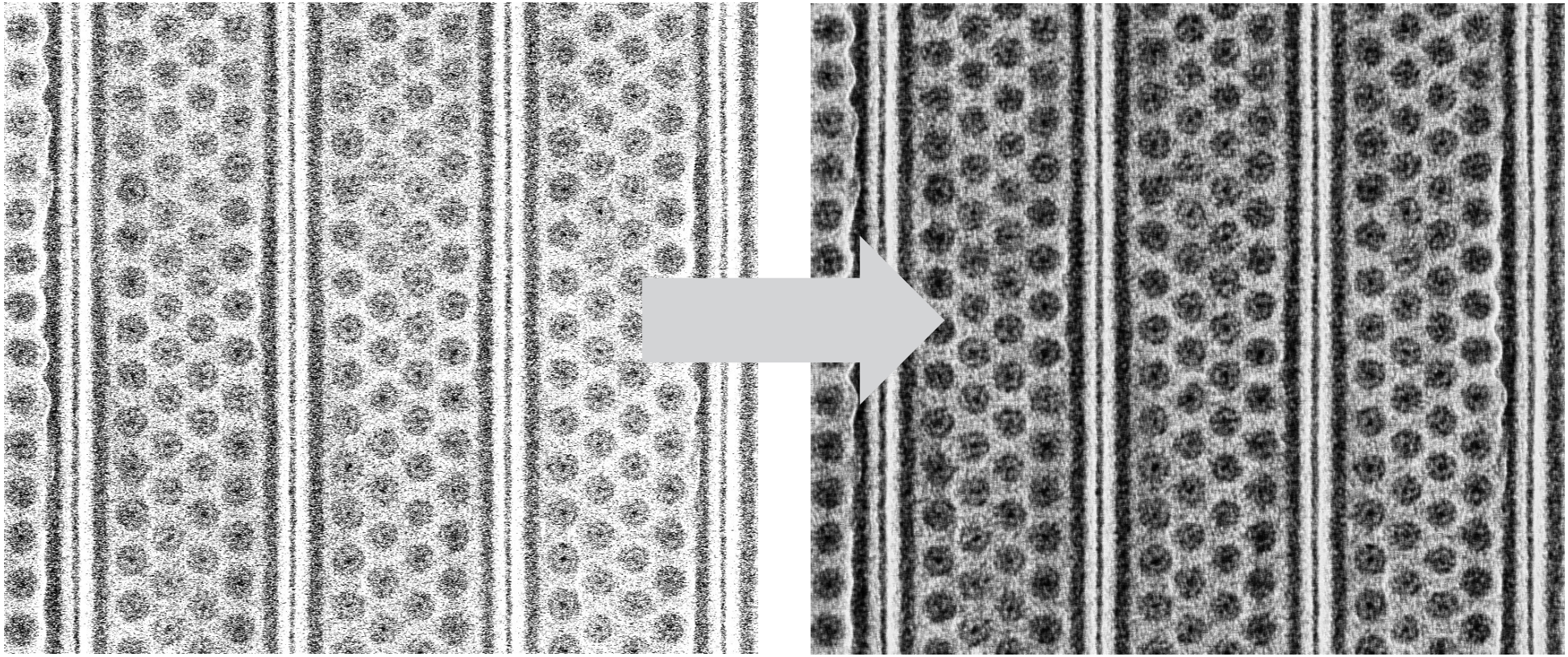


Contd.

Individual Image Frame Noise Reducer (NR) model: 3D NAND (Verios SEM) trained

Original Single Frame

After super resolution enhancement

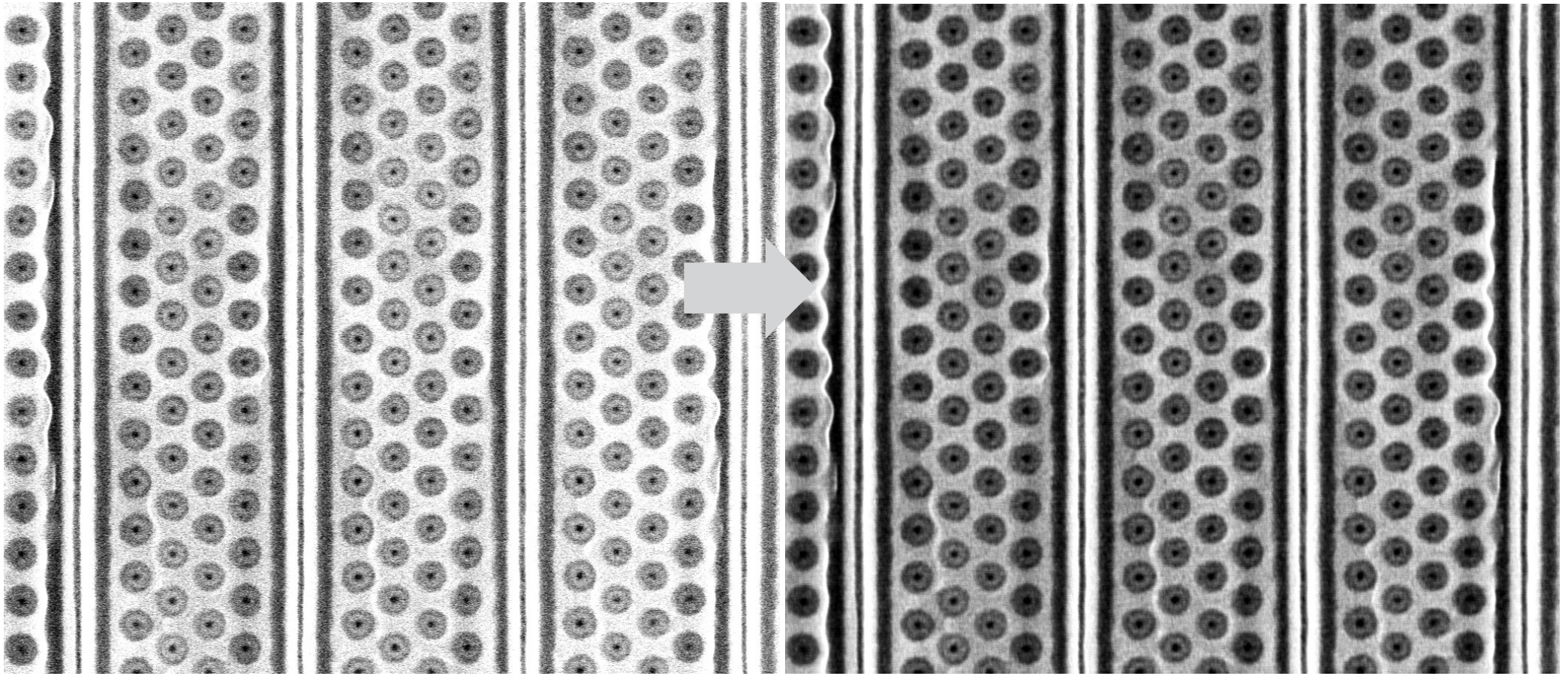


Multiple frames (of very low dwell time) are enhanced by NR model prior to DCFI

DCFI of image frames before and after NR model application:

Before

After



We will rework the NR training to reduce the amount of blur

Image before and after NR model application(reintroducing low-level noise to “after” result from original data):

Using original image frames only

Using original + improved image frames

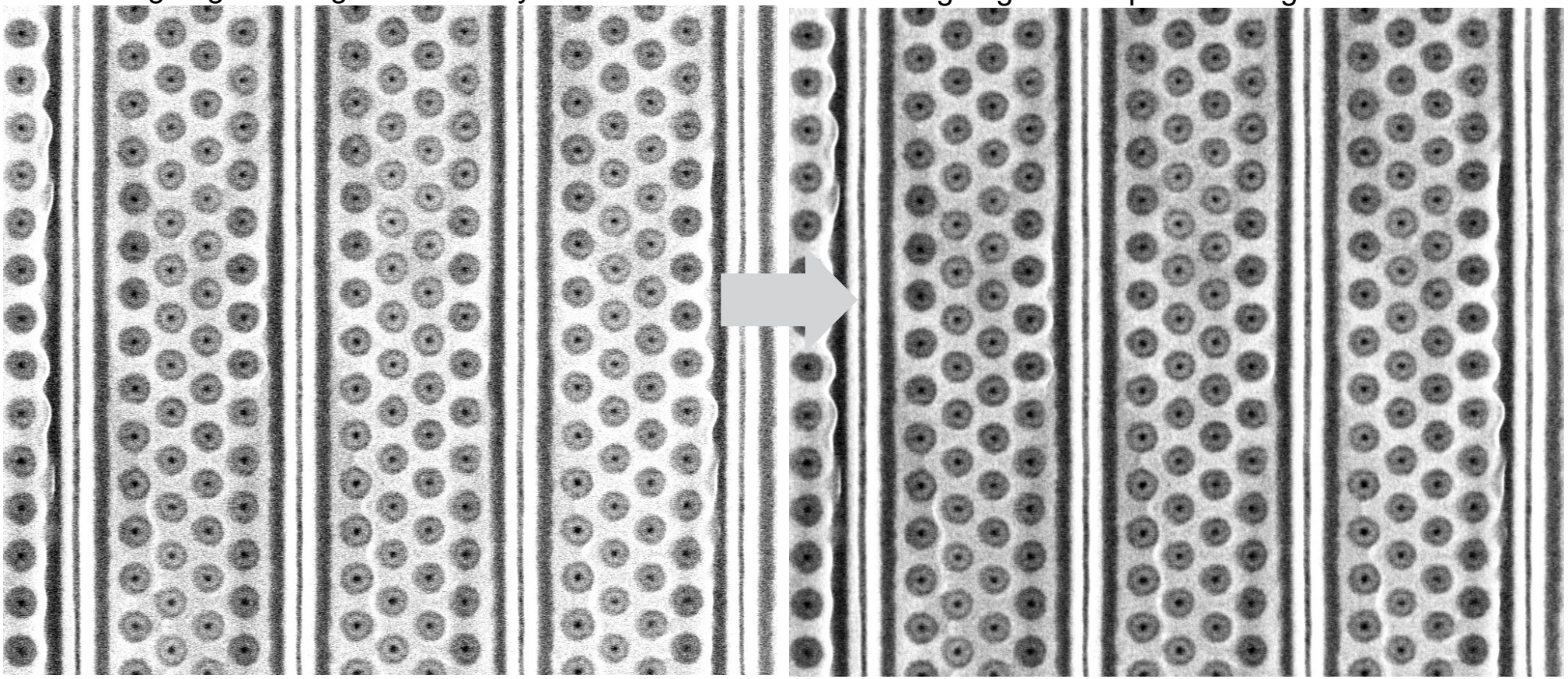


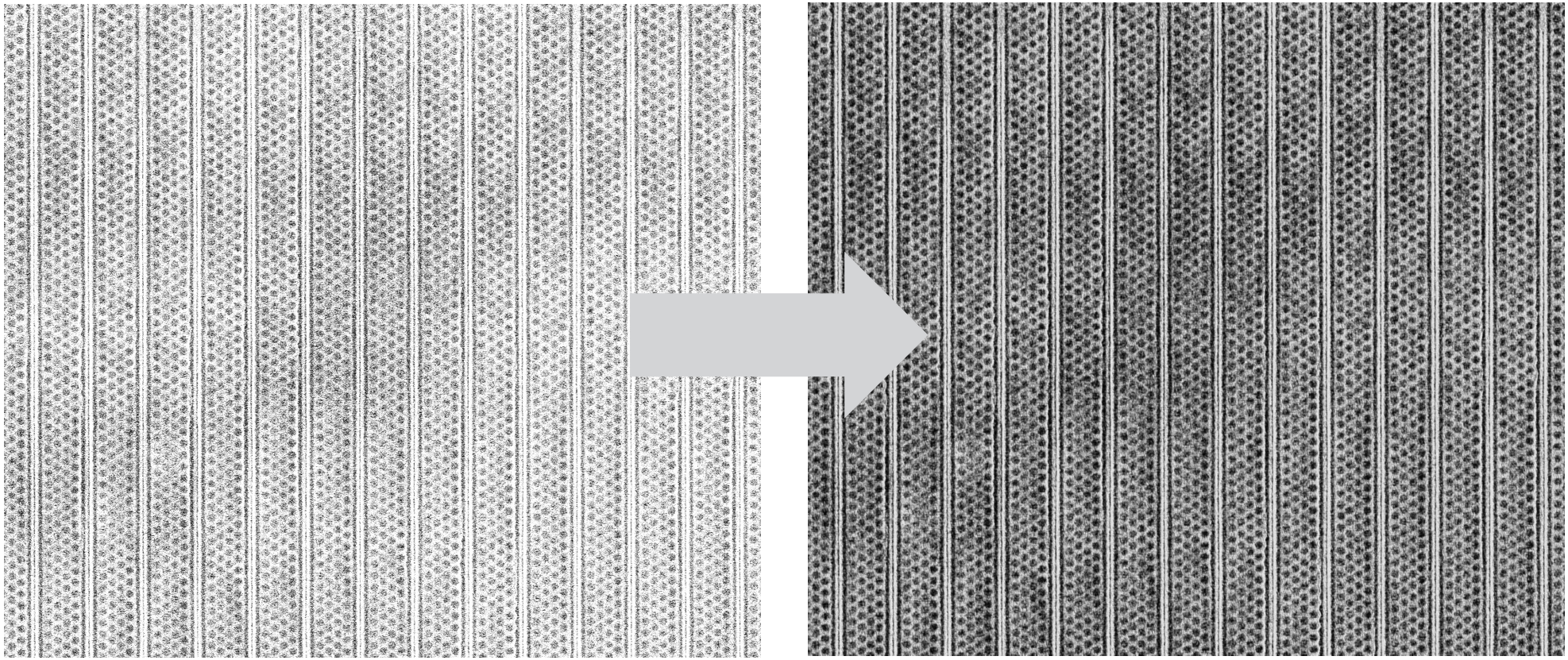
Image frames from both before and after the application of super resolution are used to construct a single DCFI image. This is intentionally done to reintroduce characteristic SEM noise to the final image at a low level to get a better “appearance”.

If you zoom 200%, you will see pixel level effect of super resolution

Individual Image Frame Noise Reducer (NR) model: 3D NAND (Verios SEM) trained

Original Single Frame

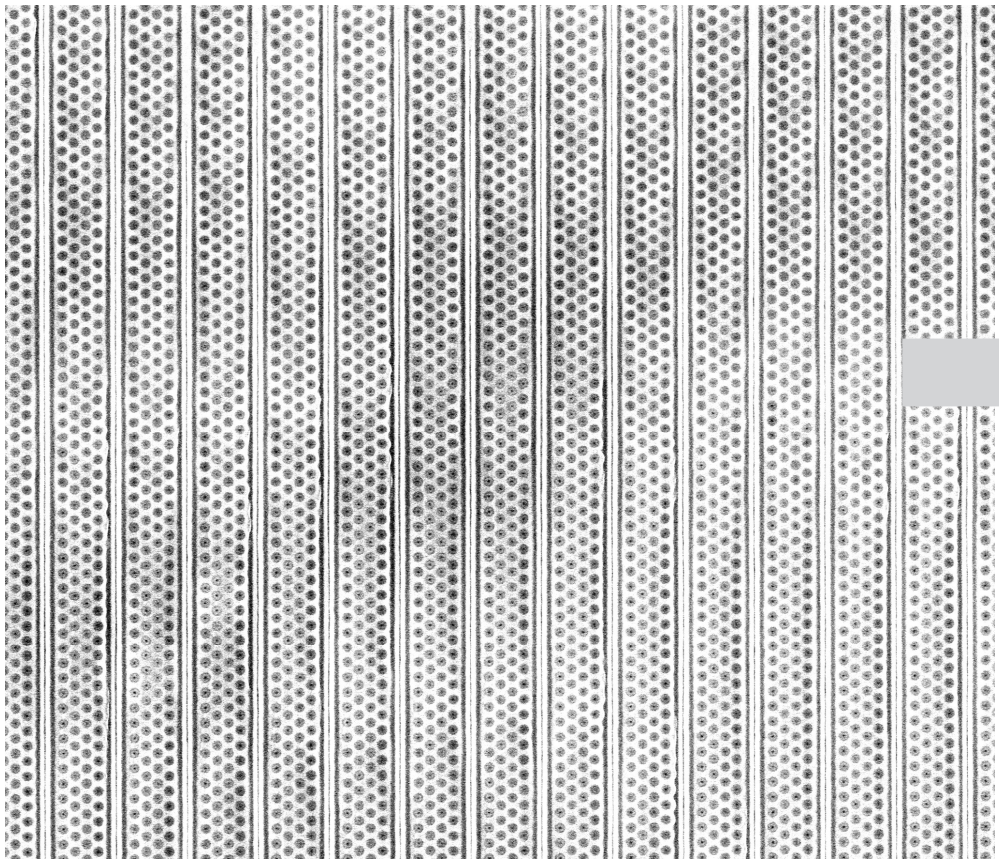
After noise reduction enhancement



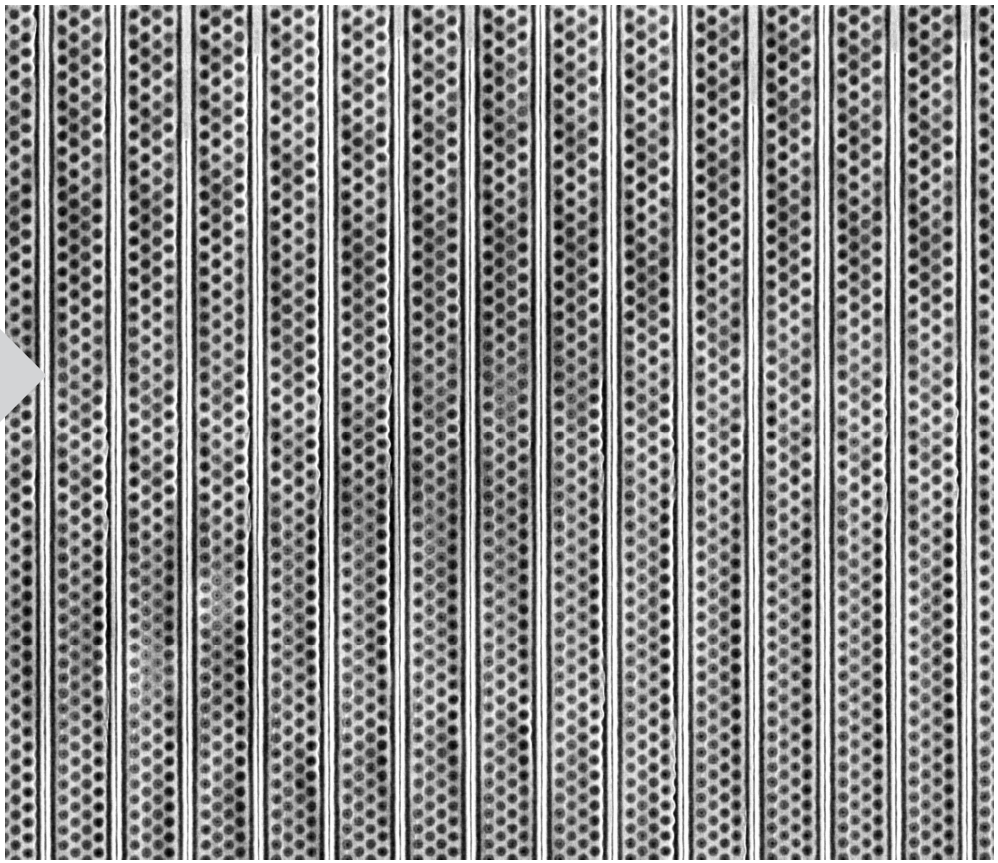
Multiple frames (of very low dwell time) are enhanced by NR model prior to DCFI

DCFI of image frames before and after NR model application:

Before



After

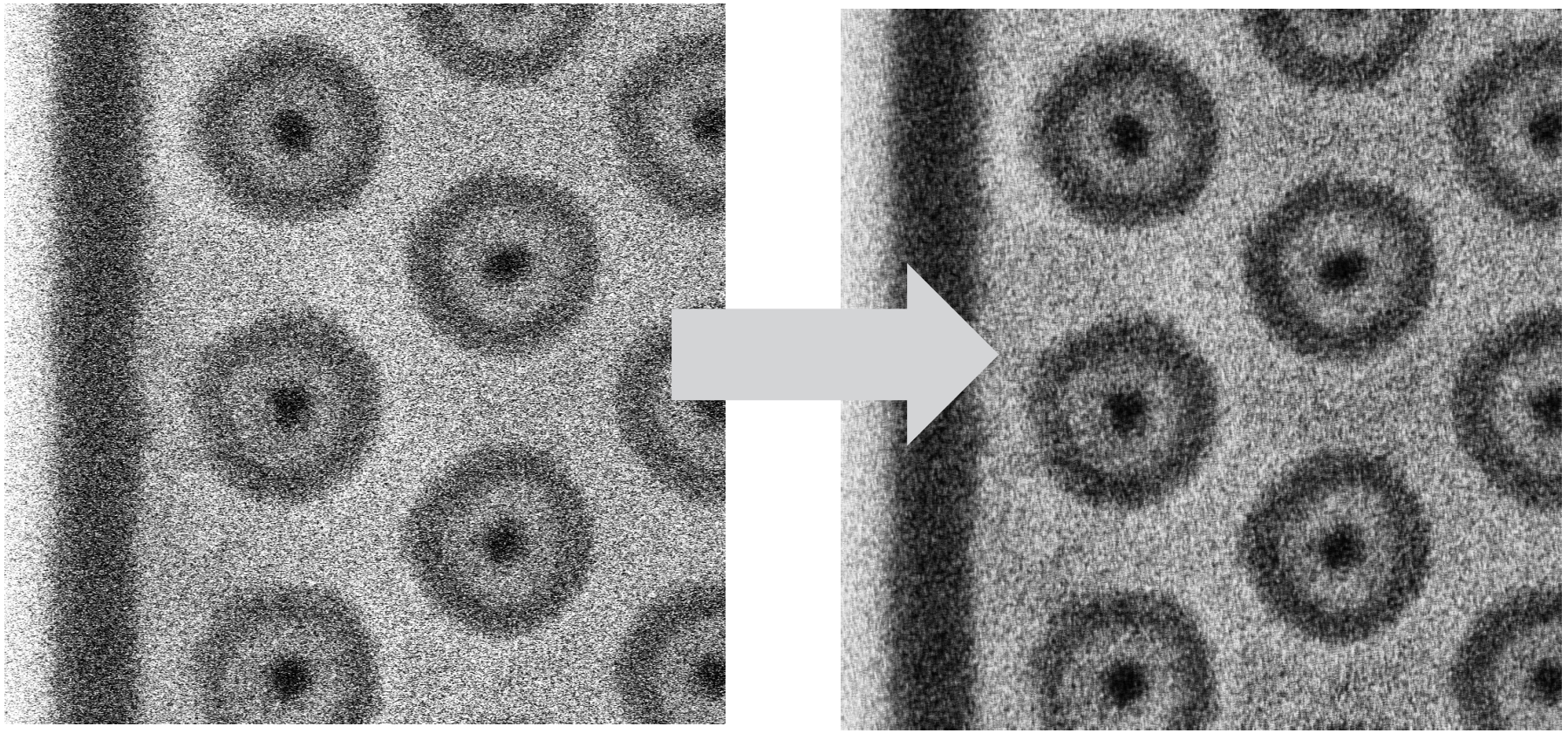


We will rework the NR training to reduce the amount of blur

Individual Image Frame Noise Reducer (NR) model: 3D NAND (Verios SEM) trained

Original Single Frame

After noise reduction enhancement



Multiple frames (of very low dwell time) are enhanced by NR model prior to DCFI

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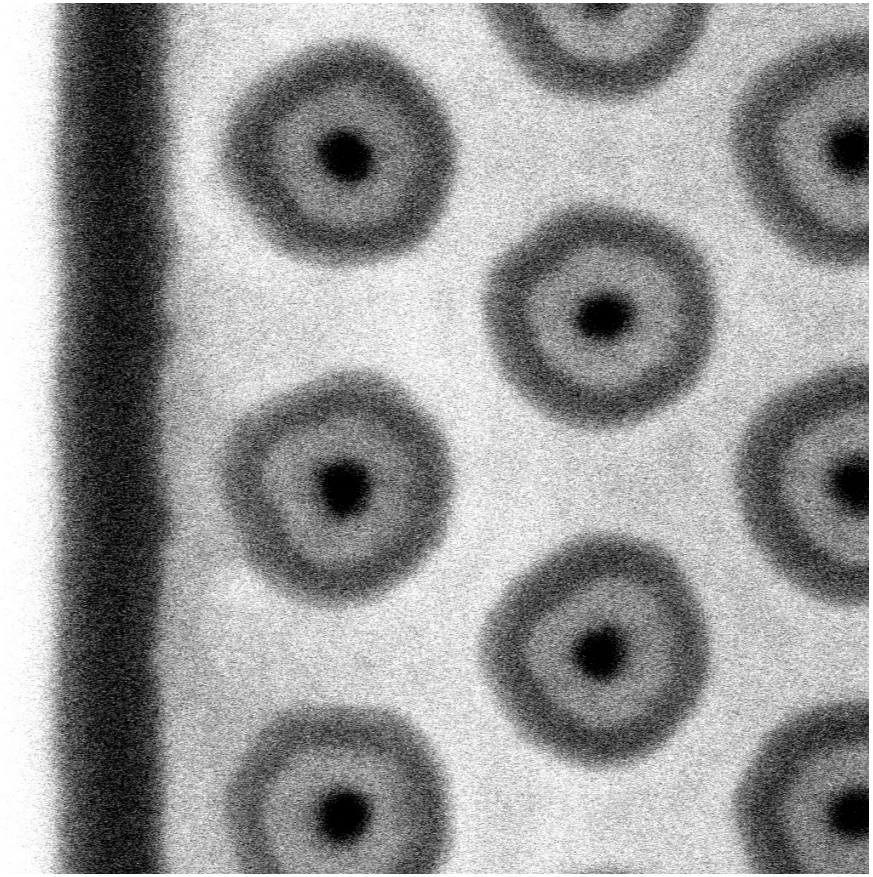
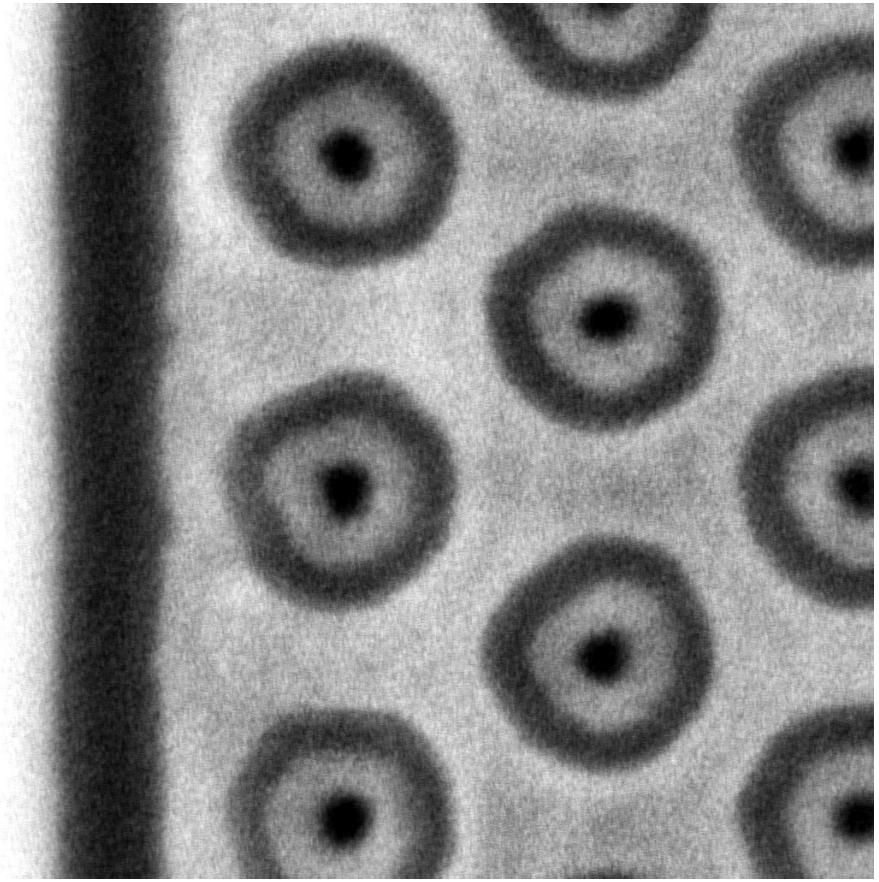
DCFI of image frames before and after NR model application:

Before



After

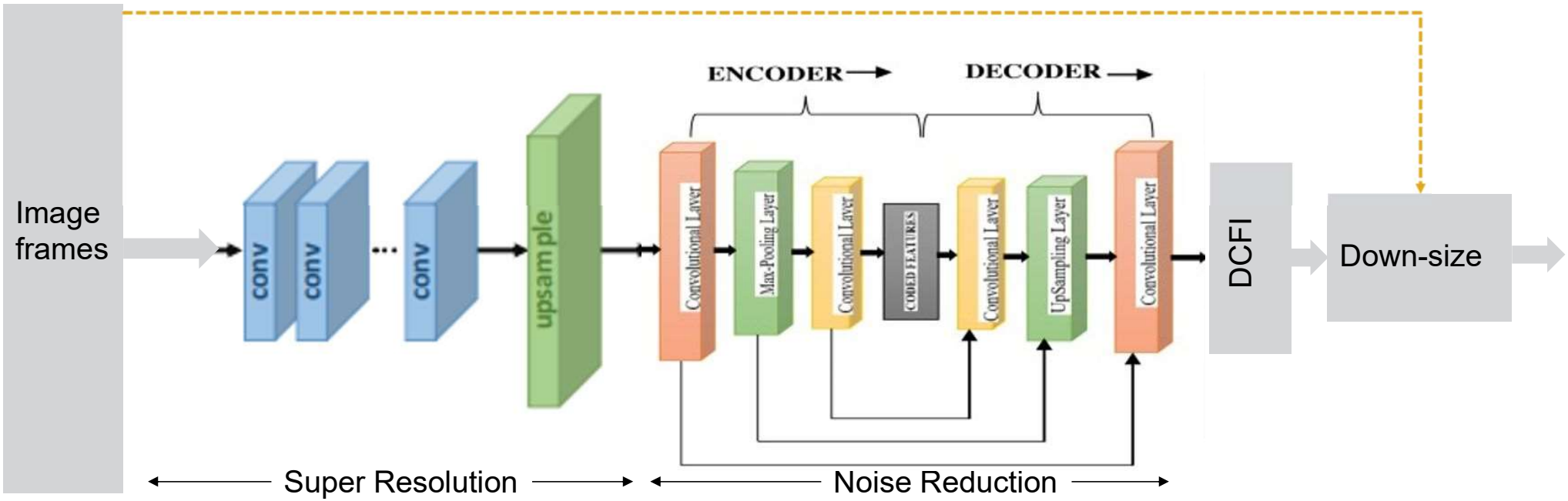


We will rework the NR training to reduce the amount of blur

Conclusions on the Noise Reducer Model:

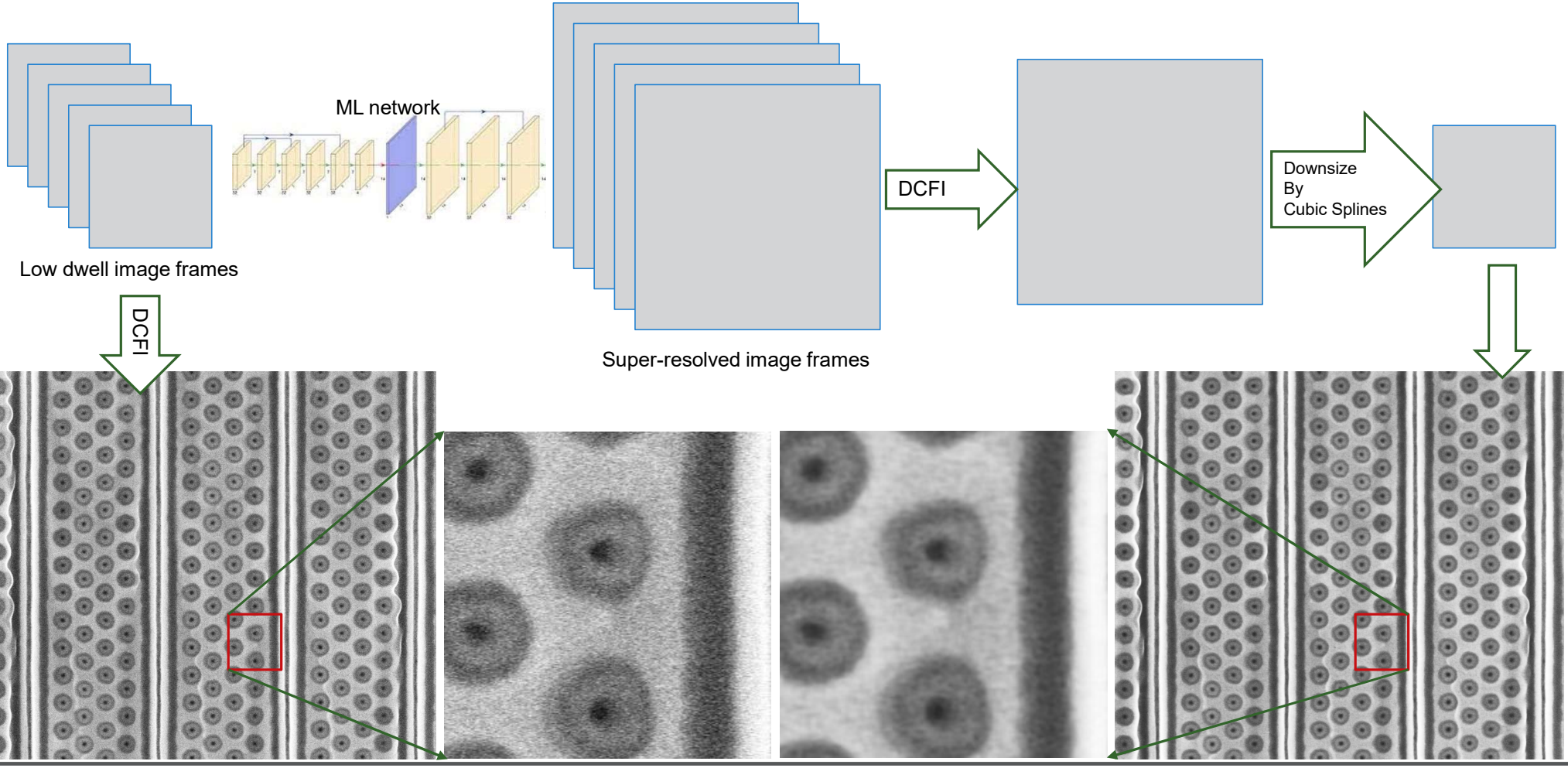
- Noise reducer model when applied on original image frames has performed well
- Fast training and fast execution make this model more attractive.
- Some experiment in reworking the model might be necessary to reduce the blur and reduce large contrast variation possibilities.
- Appears to carry forward image artifacts. Should be reworked and retrained to reduce this.

Using whole model



Resulting images are in next few slides.
This is a first attempt.
We have a clear path to rework and get better results

Idea



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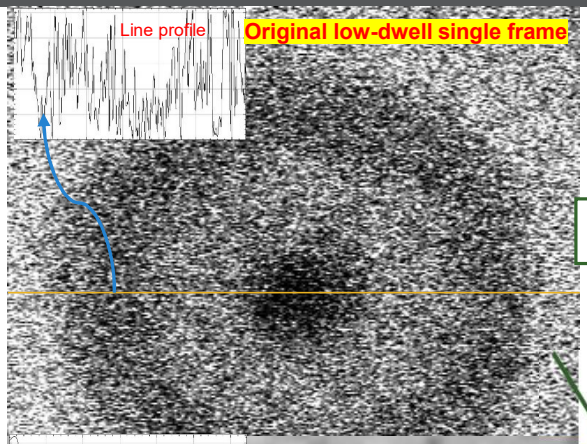
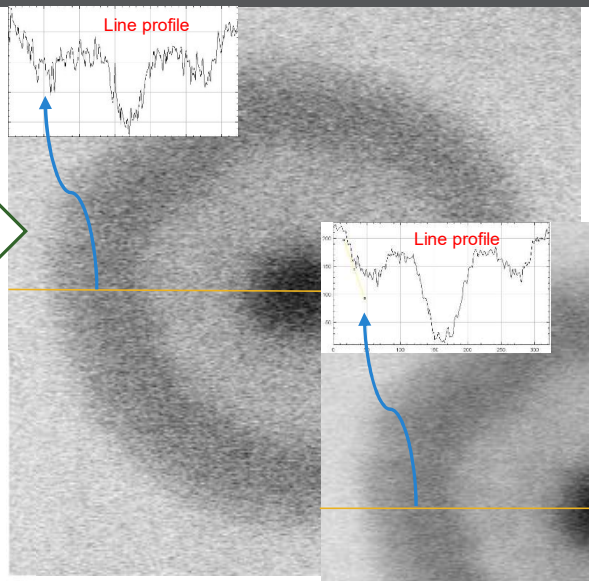
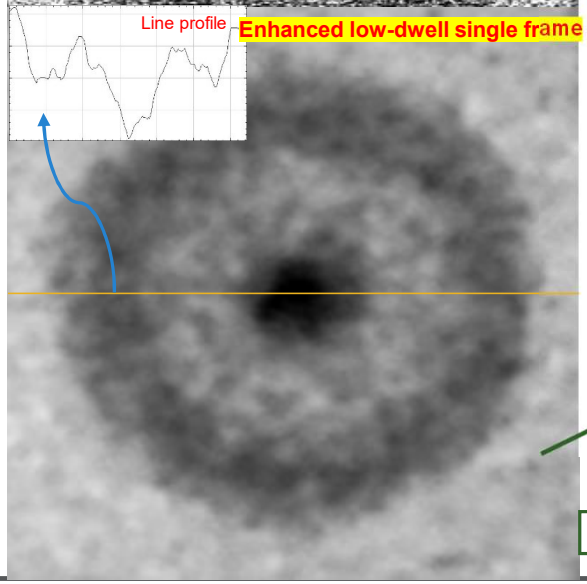
Can be implemented at individual object level for precision metrology:

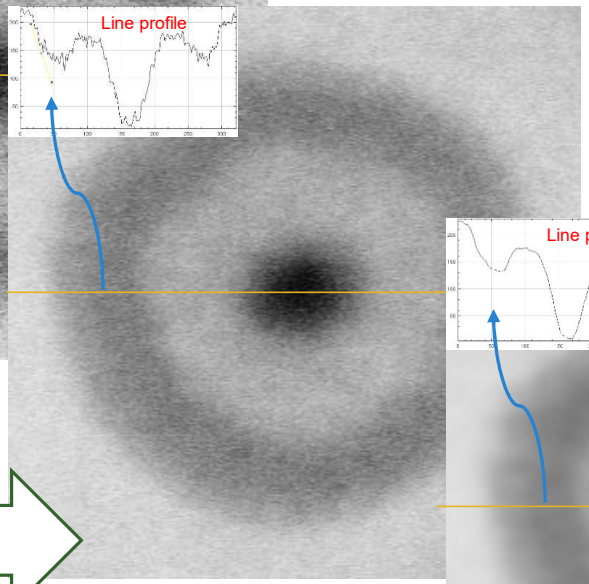


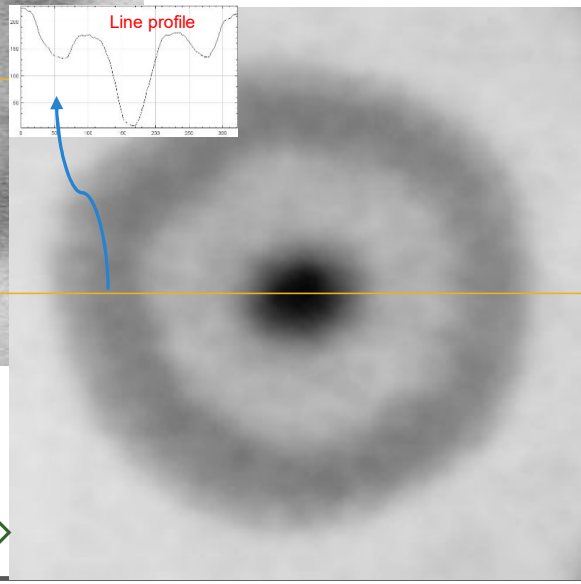
DCFI
Original frames only





DCFI
Original and super-resolved frames





DCFI: Super resolved frames only

Super-resolved images can have
1. more pixels per square unit area that would facilitate sub-pixel resolution in CD measurement.
2. High SNR and hence better accuracy.
3. Can be applied before DCFI, after DCFI and/or during metrology

* Working on restoring the loss of crispness

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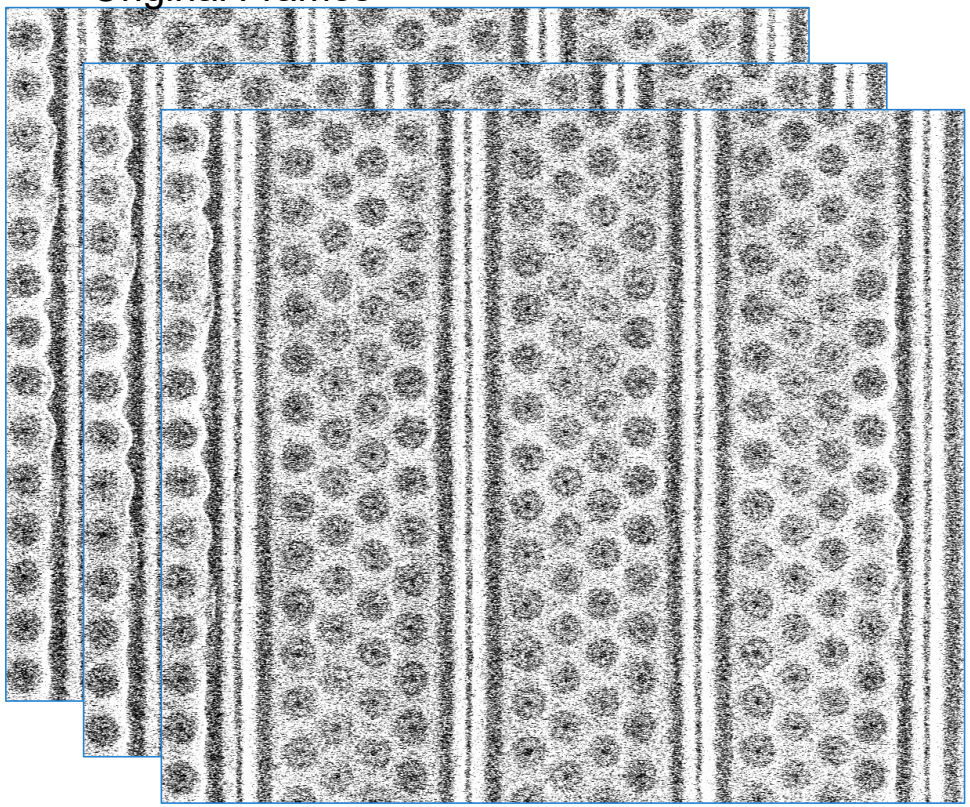
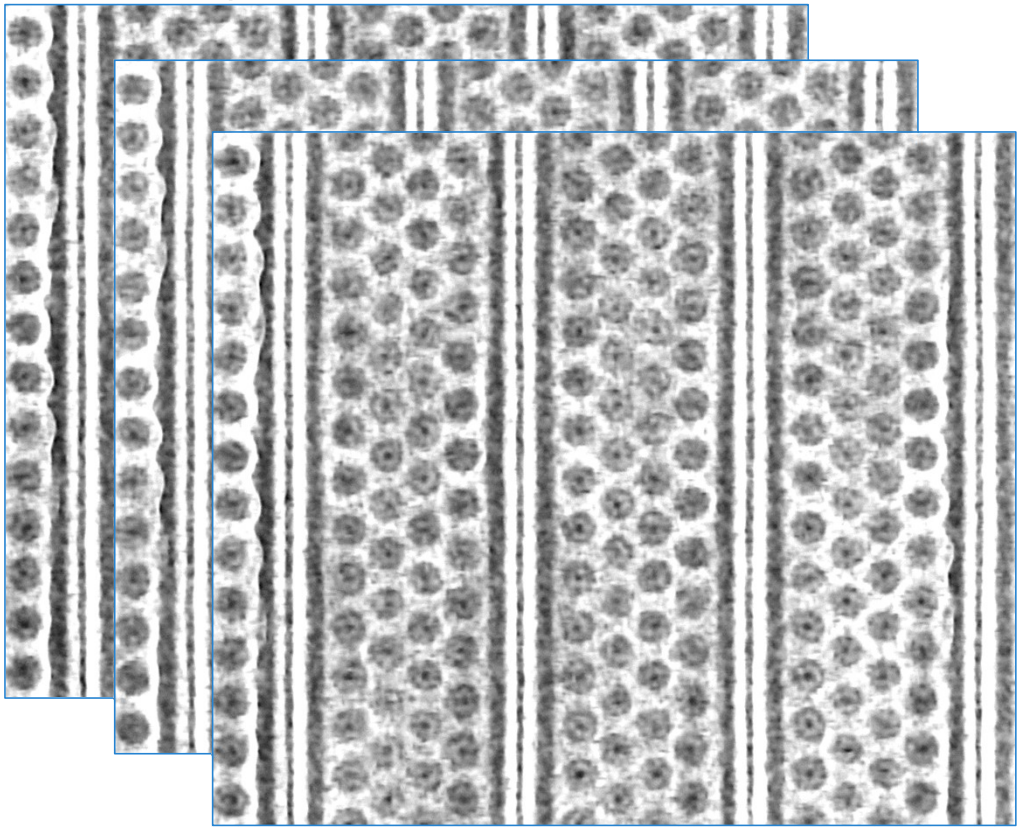
Individual Image Frame Super Resolution (SR) model: 3D NAND (Verios SEM) trained

Original Frames



After super resolution enhancement



DCFI of image frames before and after SR model application:

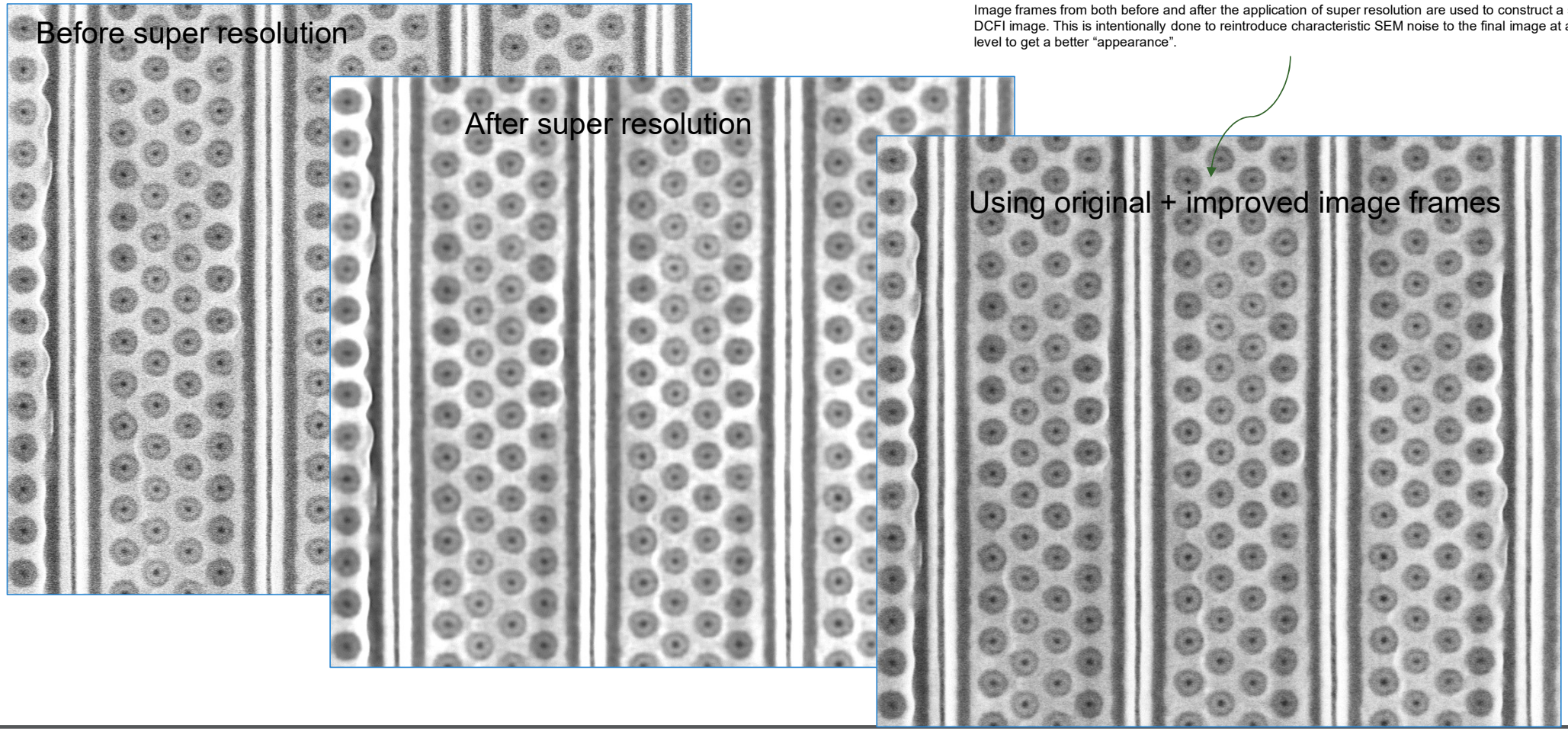
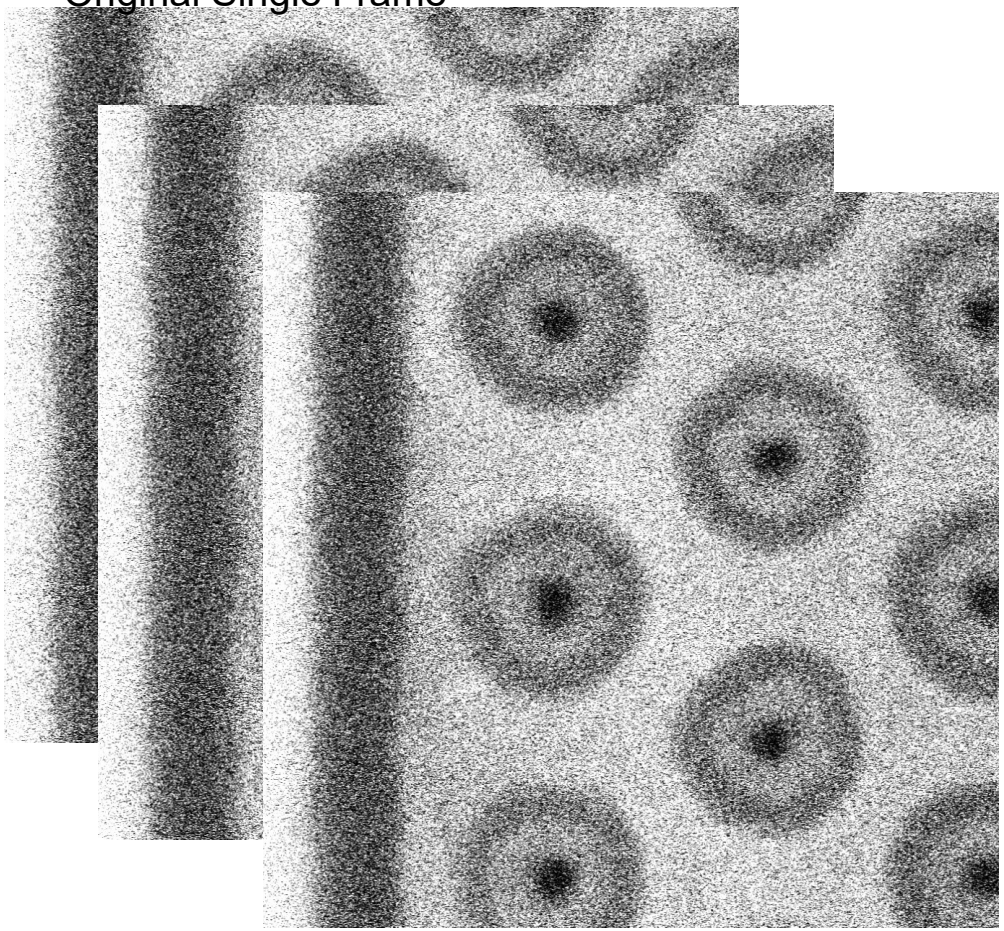


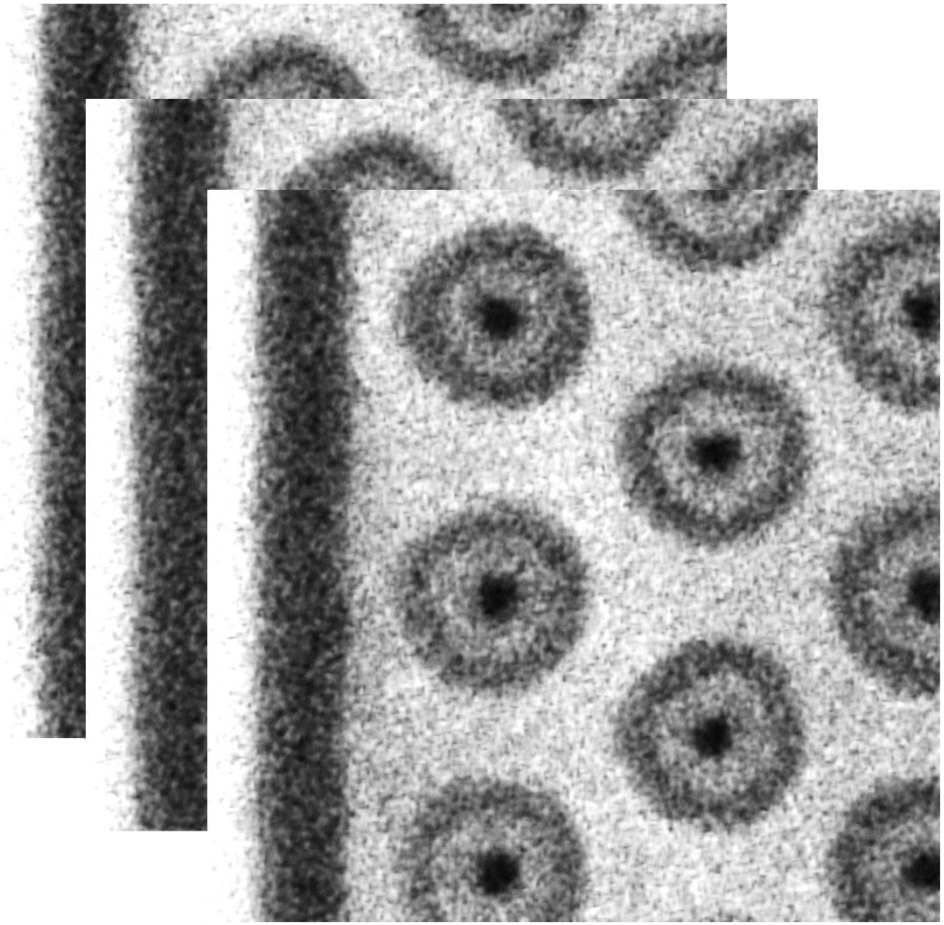
Image frames from both before and after the application of super resolution are used to construct a single DCFI image. This is intentionally done to reintroduce characteristic SEM noise to the final image at a low level to get a better “appearance”.

Individual Image Frame Super Resolution Noise Reducer (SRNR) model: 3D NAND (Verios SEM) trained
(Here we extend the super-resolution network to further reduce the noise in individual frames and hence SRNR model)

Original Single Frame

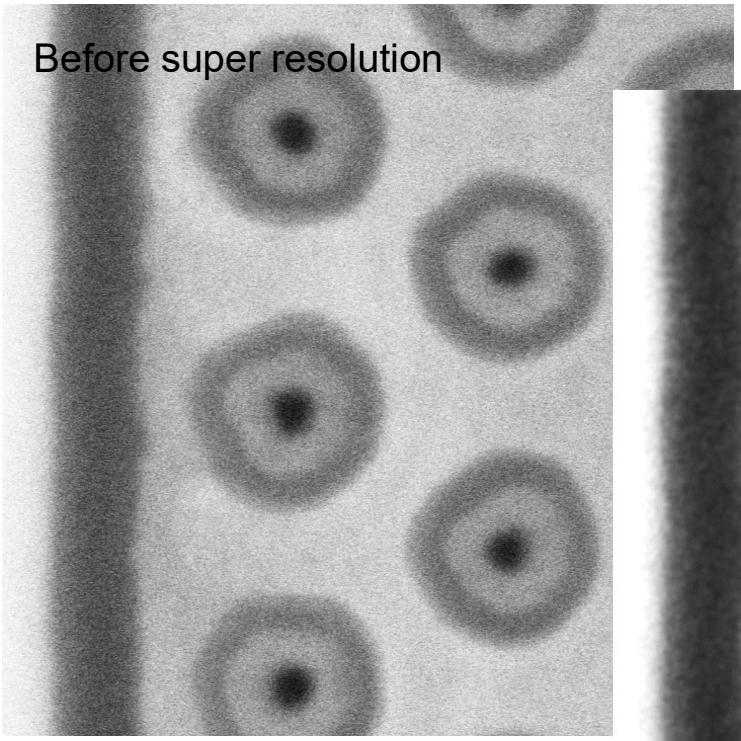


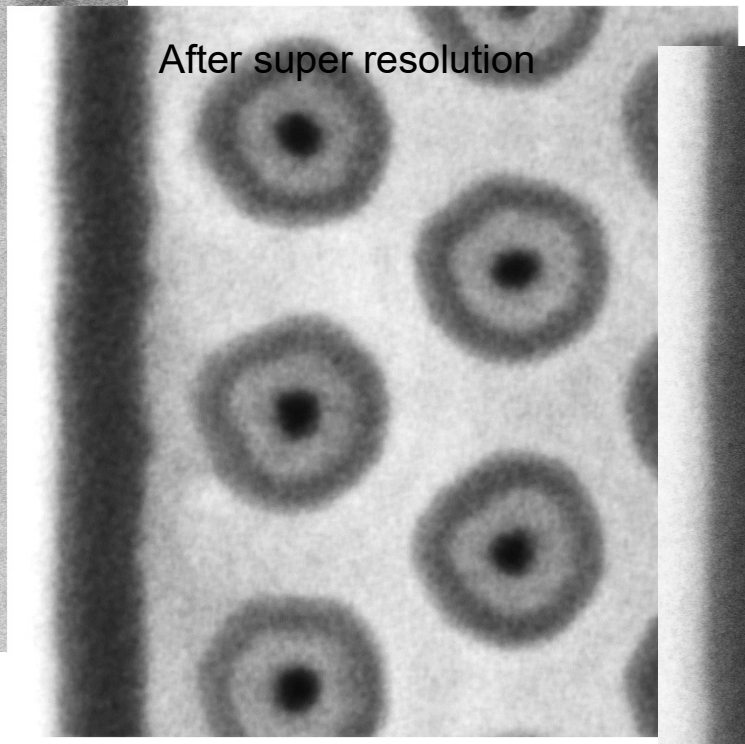
After super resolution enhancement



Multiple frames (of very low dwell time) are enhanced by SRNR model prior to DCFI

Image before and after SRNR model application:





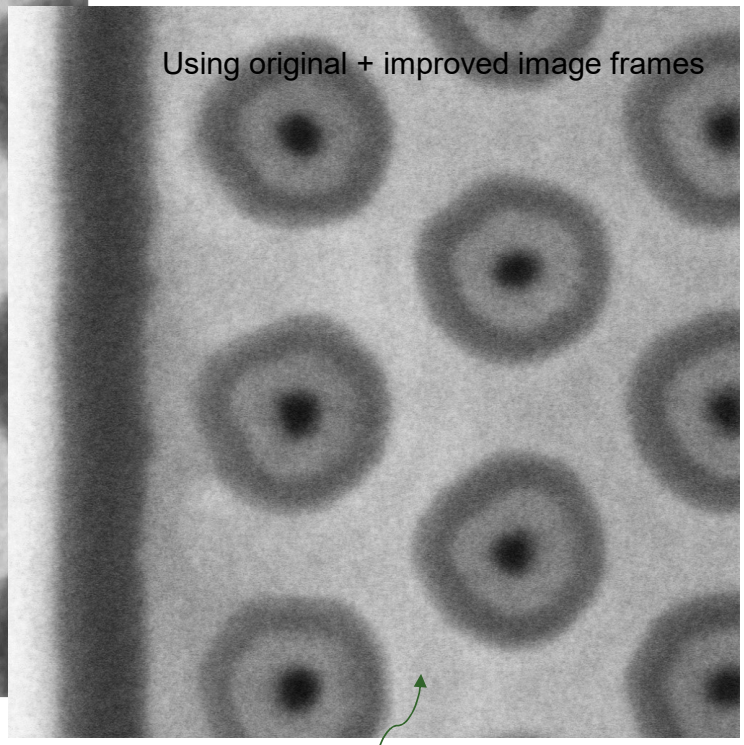


Image frames from both before and after the application of super resolution are used to construct a single DCFI image. This is intentionally done to reintroduce characteristic SEM noise to the final image at a low level to get a better “appearance”.

Conclusions (for version -2.0)

- NRSR results can be improved further
- Individual SR modelling or NR modelling appear to have achieved equal or better results.

1. Training to be done on high quality image data
2. Different models are to be reconstructed for different resolution (as in the image acquisition GUI menu)
3. More research will be done to reduce blurring
4. Different super resolution models will be tested in the coming days
5. May end-up choosing only SR model or only NR model as a sufficient process instead of SRNR or NRSR pipelines that are memory and time consuming.