A SHARP TOOL FOR CURRENT AND FUTURE NODES OF EUV LITHOGRAPHY

SHARP High-NA actinic Reticle Review Project

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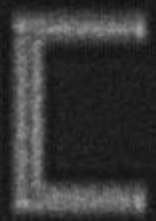
2019 International Workshop on EUV Lithography
Lawrence Berkeley National Lab, Berkeley, June 11

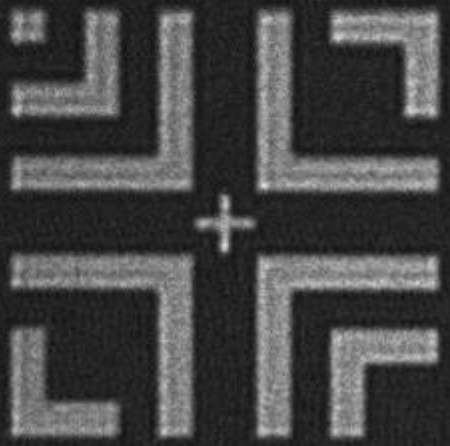
BERKELEY LAB
Lawrence Berkeley National Laboratory

SHARP

CXRO
THE CENTER FOR X-RAY OPTICS

Source:	Synchrotron
Optics:	Zoneplate lenses
4×NA:	0.25–0.625
Illuminator:	Programmable
Navigation:	2-µm position accuracy
Throughput:	up to 24 sites/hour

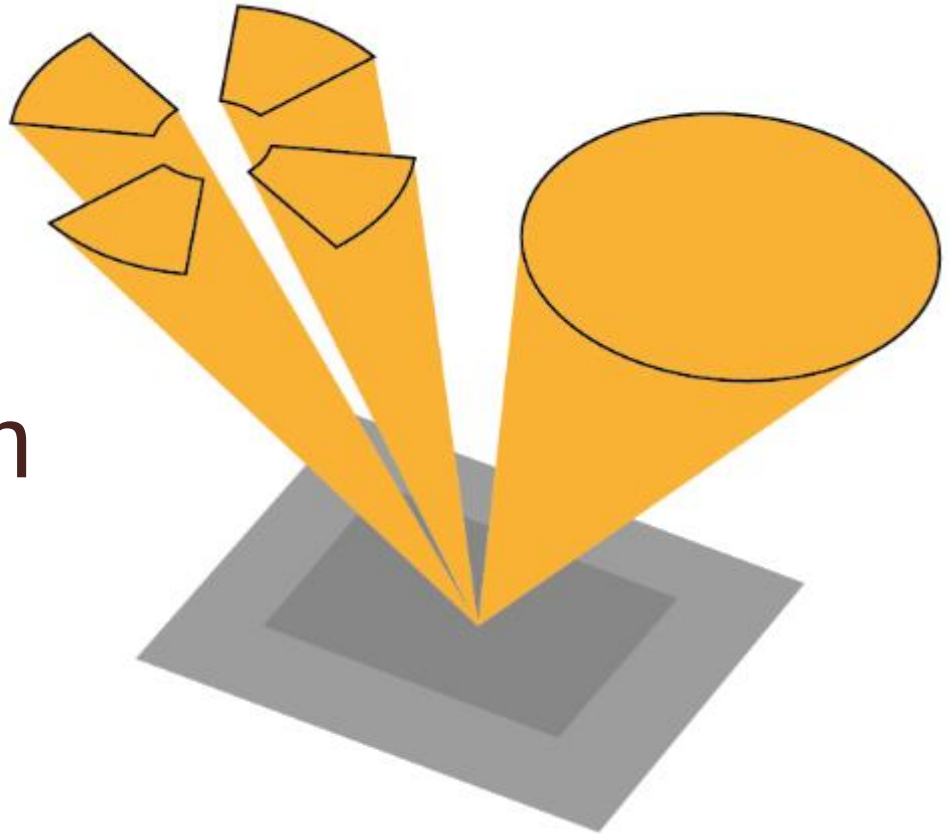




EUV SMO
01
LINES

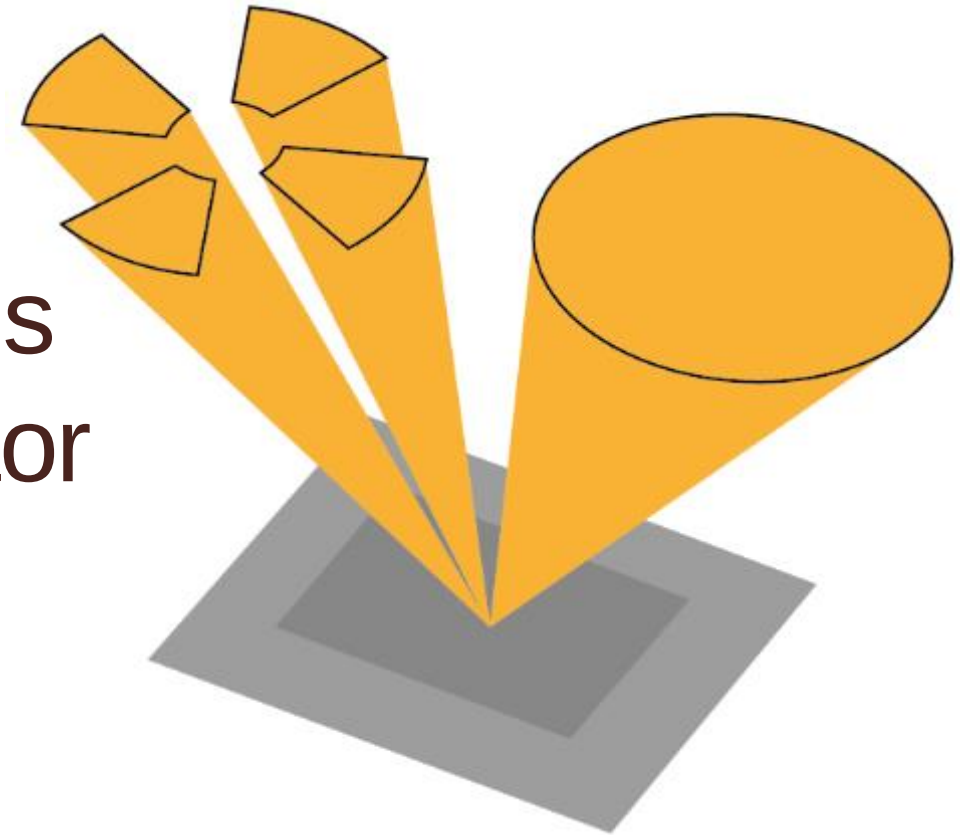
How much light do you actually need?

Source angular spectrum

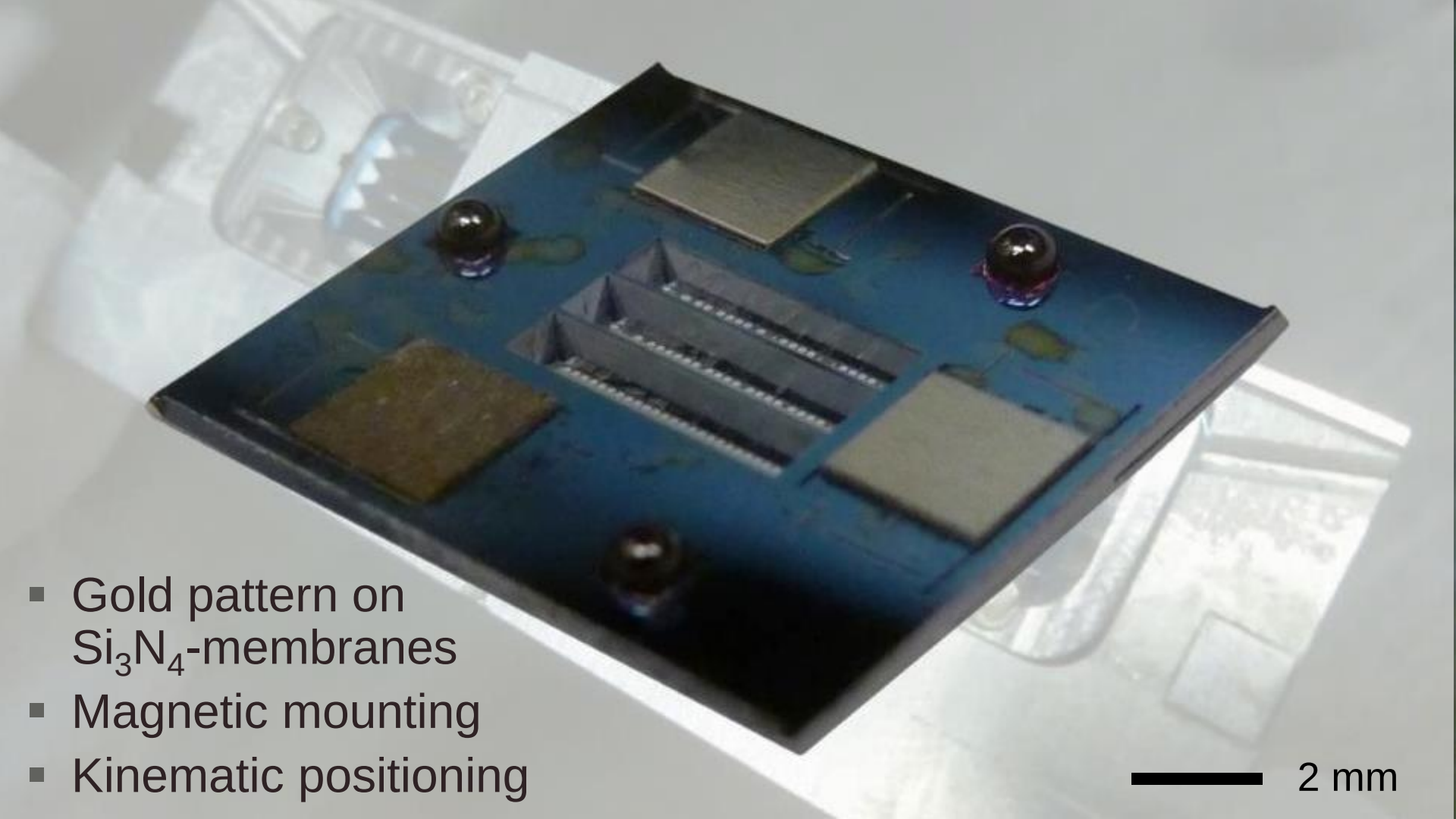


Aperture

Fourier synthesis illuminator



Zoneplate lens

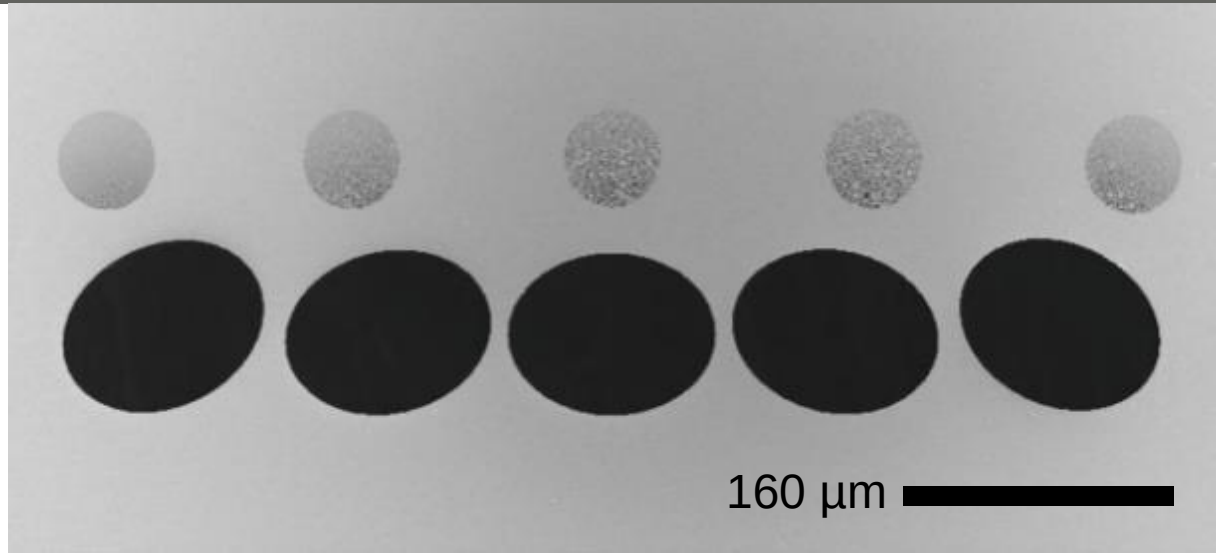


- Gold pattern on Si_3N_4-membranes
- Magnetic mounting
- Kinematic positioning

Zoneplates

Standard Zoneplates:

- 0.25 to 0.625 4xNA
- 6° to 10° CRA
- 5 azimuthal angles



Chip B

- Zernike Phase Contrast
- Differential Interference Contrast
- Stereoscopic imaging
- Cubic Phase Modulation

0.625 4xNA:

- 22-nm hp resolution on the mask
- 5.5 nm hp resolution wafer scale (for a 4x system)

Zoneplates

Standard Zoneplates:

- 0.25 to 0.625 4xNA
- 6° to 10° CRA
- 5 azimuthal angles

Chip B

- Zernike Phase Contrast
- Differential Interference Contrast
- Stereoscopic imaging
- Cubic Phase Modulation

Chip C

- Anamorphic zoneplates
- 0.55 4x/8xNA
- 6º CRA

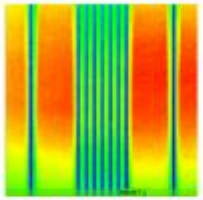
ORFEO&SHARP BEST FOCUS SHIFT AT NA0.55

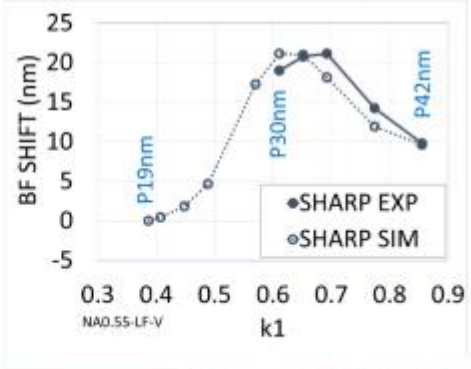
CENTRAL OF 7 BARS: SHARP EXPERIMENT VERSUS SIMULATION

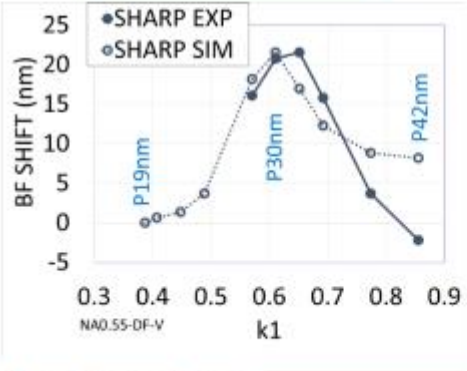
LIGHT FIELD

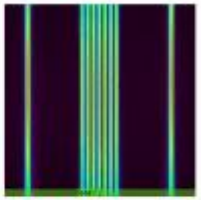
DARK FIELD

VERTICAL



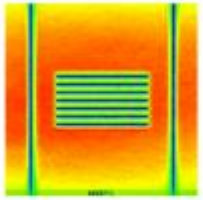


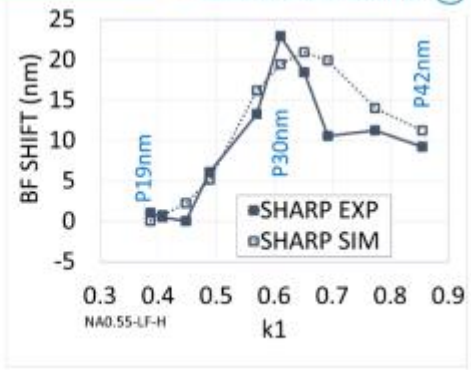


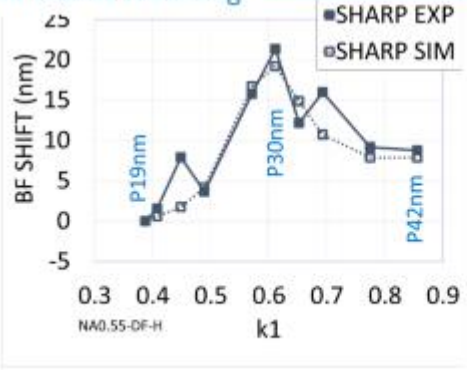


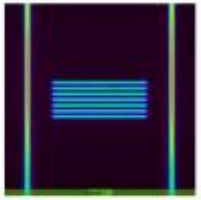
Good confidence @NA0.55: ranges and trends matching

HORIZONTAL









imec

Zoneplates

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- 6° to 10° CRA
- 5 azimuthal angles

Chip B

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Chip C

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Zoneplates

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- 0.25 to 0.625 4xNA
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Chip B

- Zernike Phase Contrast
- Differential Interference Contrast
- Stereoscopic imaging
- Cubic Phase Modulation

New Chip

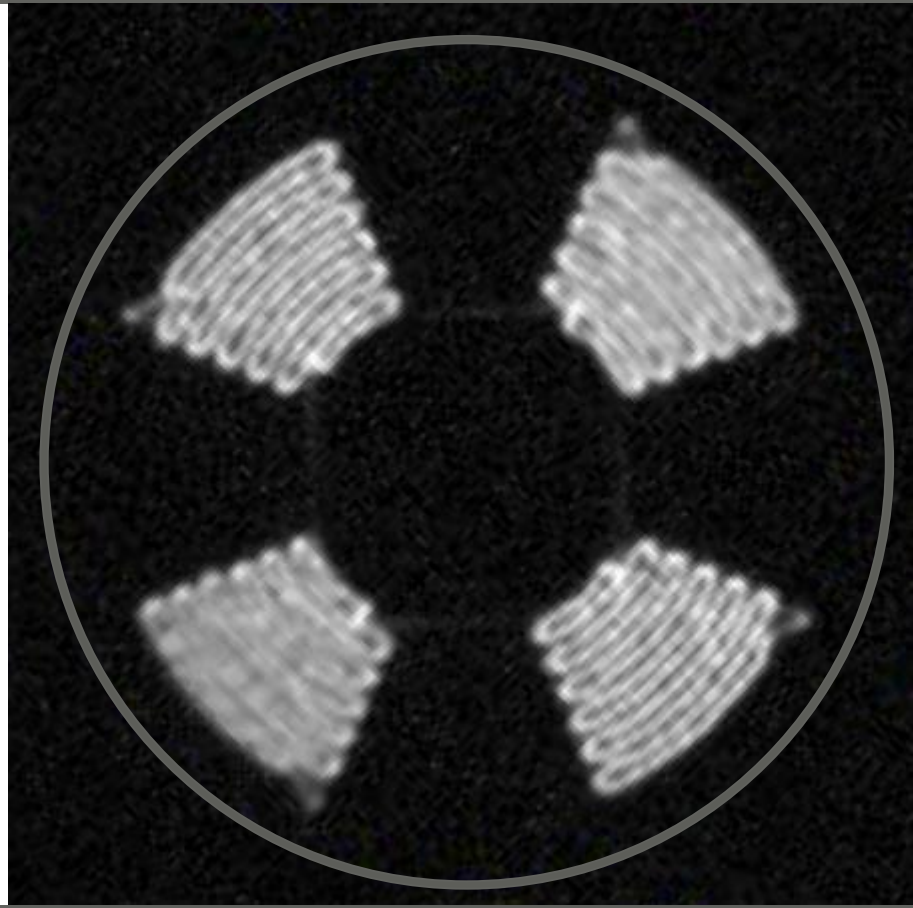
- Anamorphic zoneplates
- 0.55 4x/8xNA
- 5.355º CRA
- Central obscuration

Pupil fill

Parametric Fill

- Quasar
- 0.33 4xNA, 6° CRA

~ 10 cycles per exposure



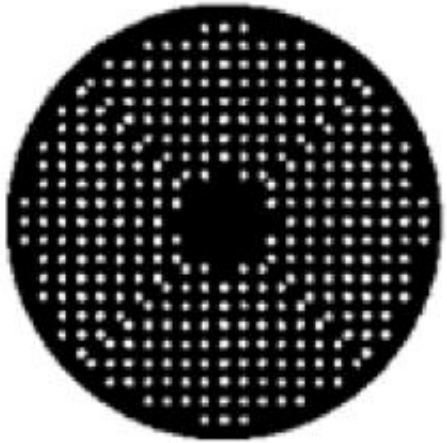
YAG image, 4mm below focus

3300 Flex Pupil

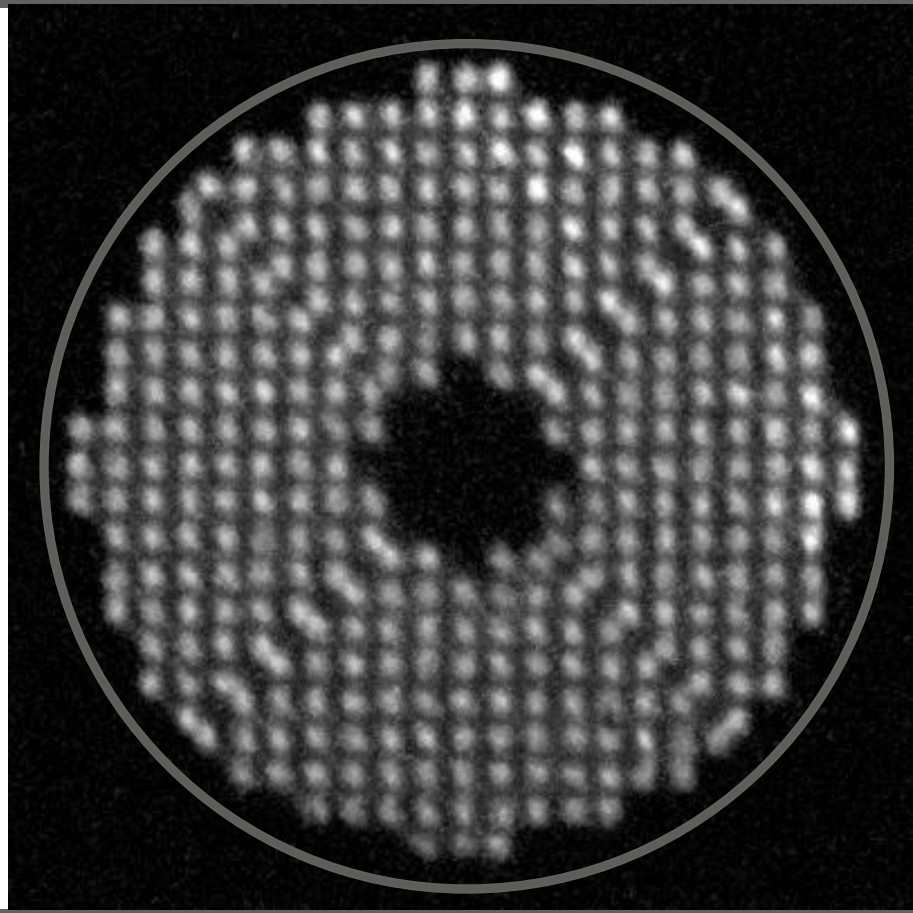
Liu, Proc. of SPIE 9048 90480Q (2014)
Meiling, Proc. of SPIE 8322**,** 83221G (2012)

Pupil fill

- Conventional
- 0.33 4xNA, 6° CRA



Liu, SPIE 90480Q (2014)

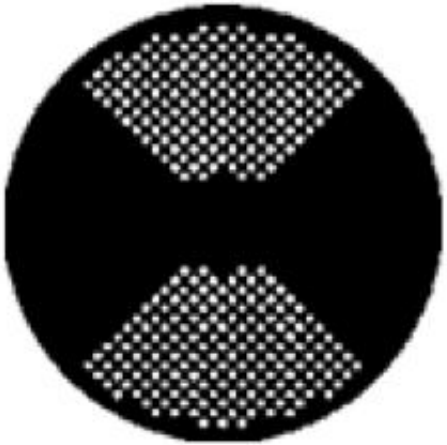


Pupil diagram

YAG image, 4mm below focus

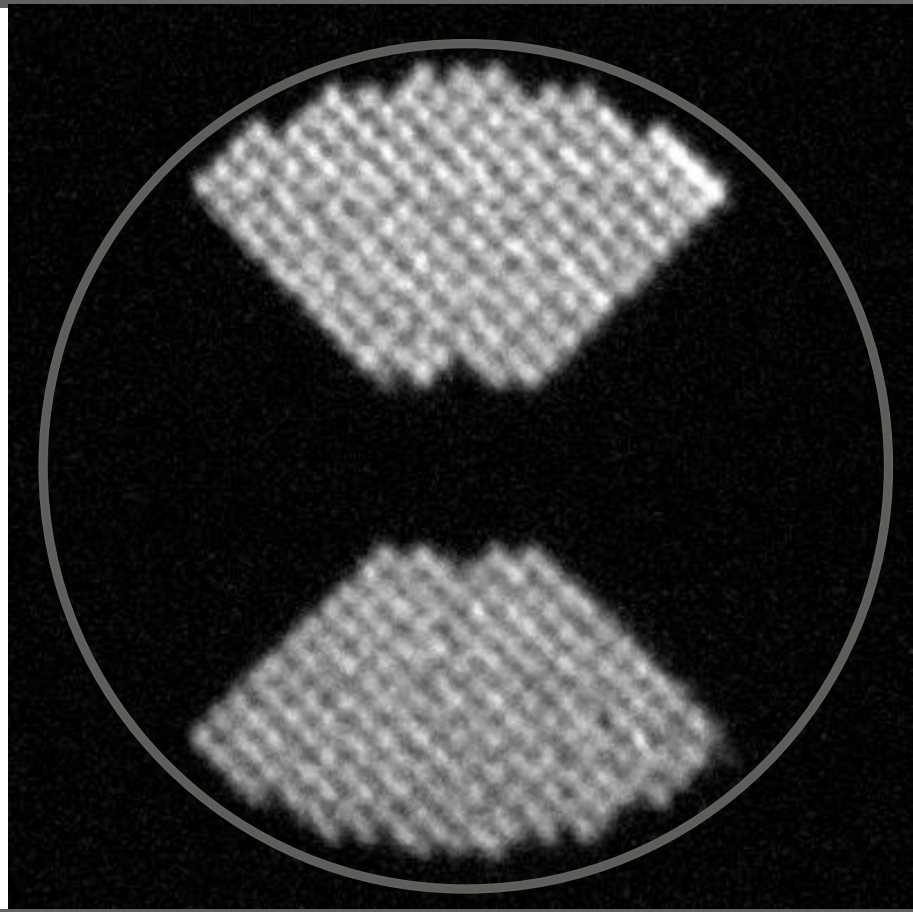
Pupil fill

- Crosspole
- 0.33 4xNA, 6° CRA



Liu, SPIE 90480Q (2014)

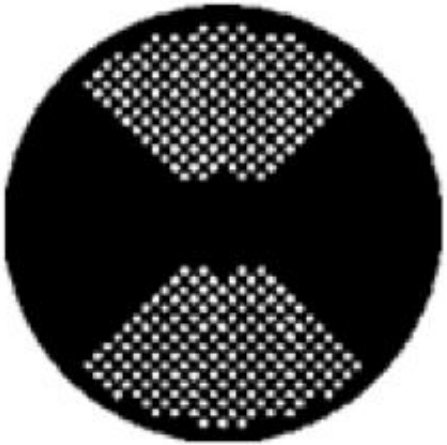
Pupil diagram



YAG image, 4mm below focus

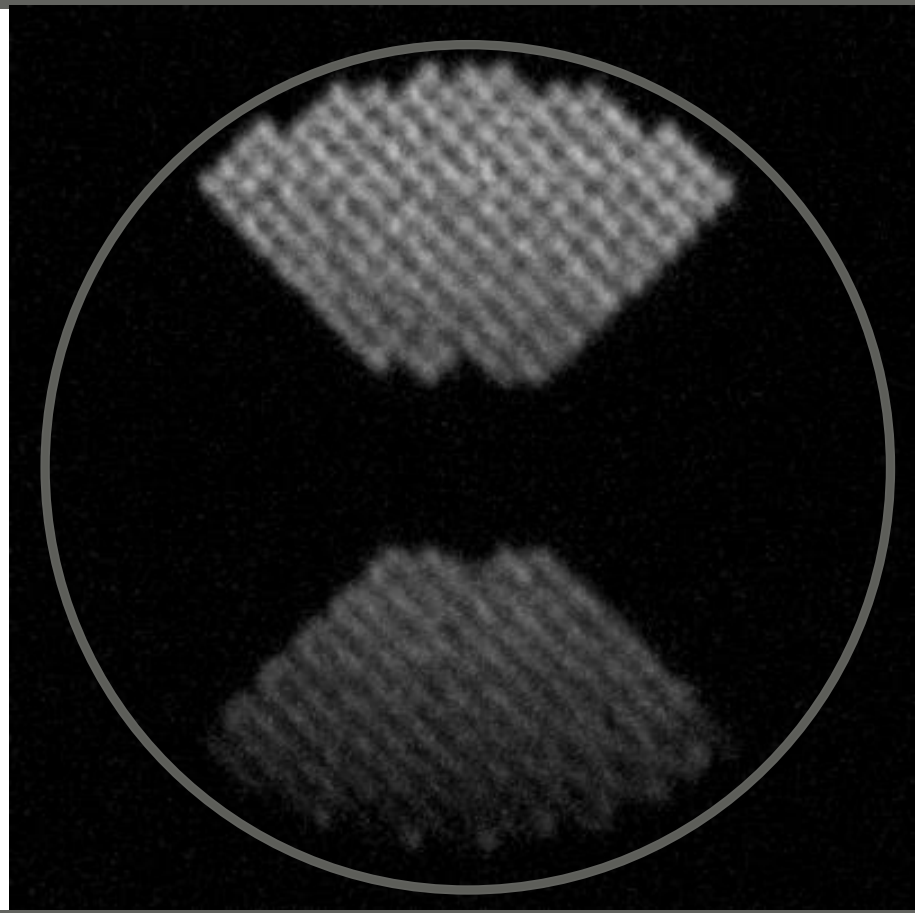
Pupil fill

- Crosspole
- 0.33 4xNA, 6° CRA



Liu, SPIE 90480Q (2014)

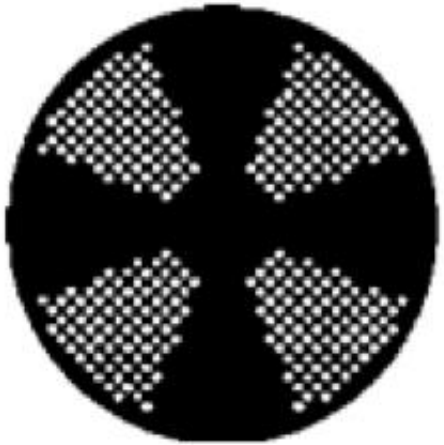
Pupil diagram



Modulation of flux in pupil channels

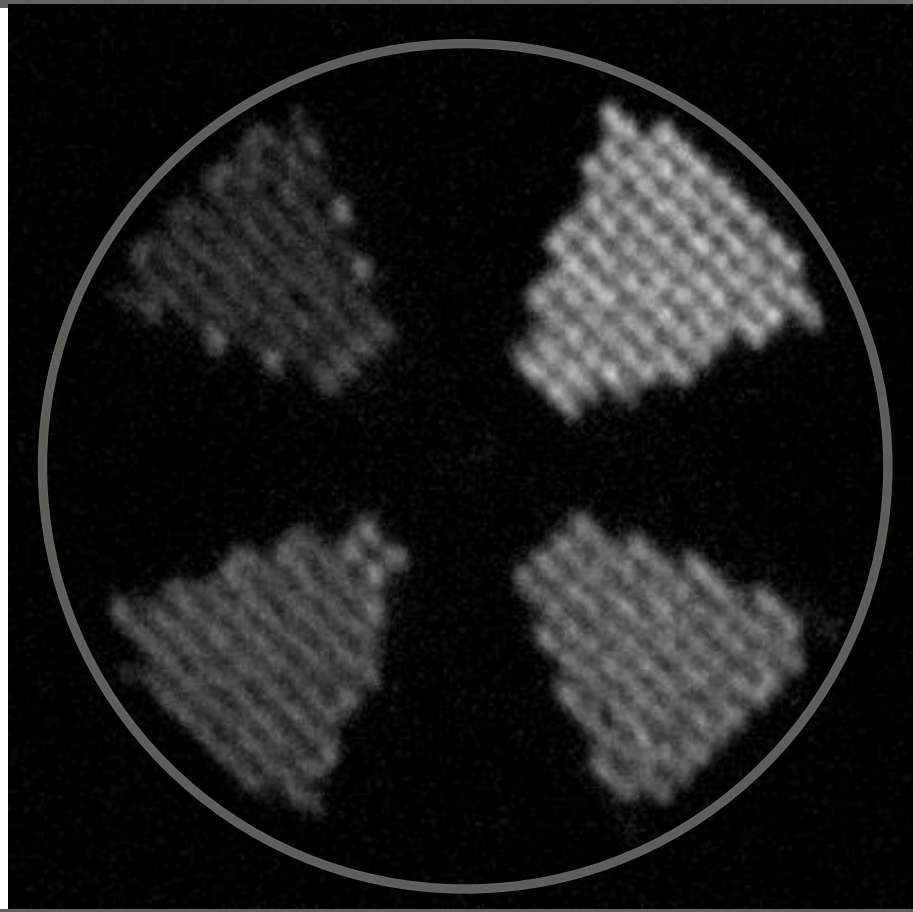
Pupil fill

- Quasar
- 0.33 4xNA, 6° CRA



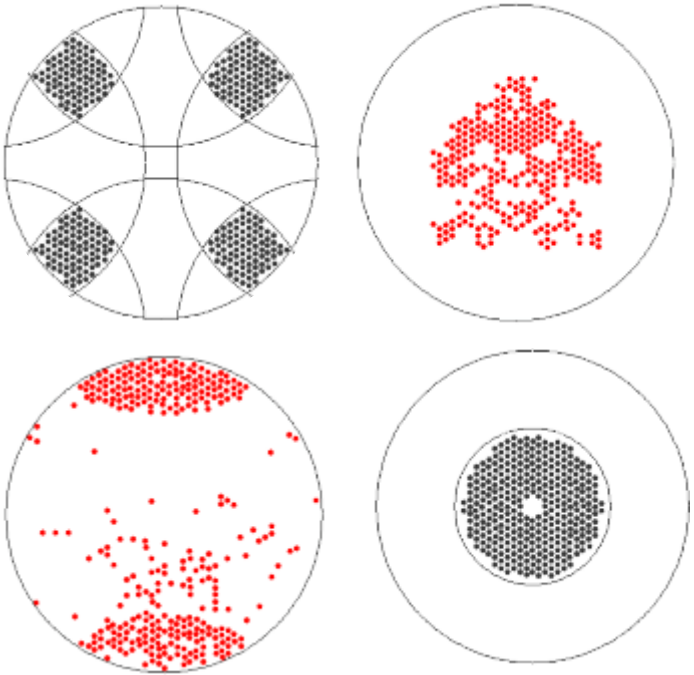
Liu, SPIE 90480Q (2014)

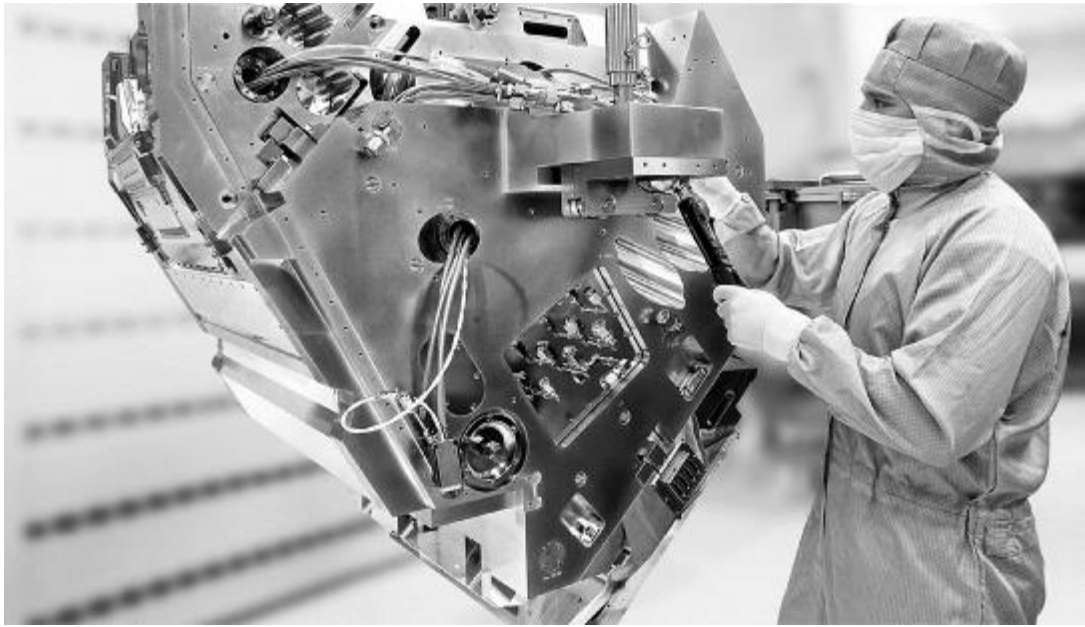
Pupil diagram



Modulation of flux in pupil channels

3400 Flex Pupil



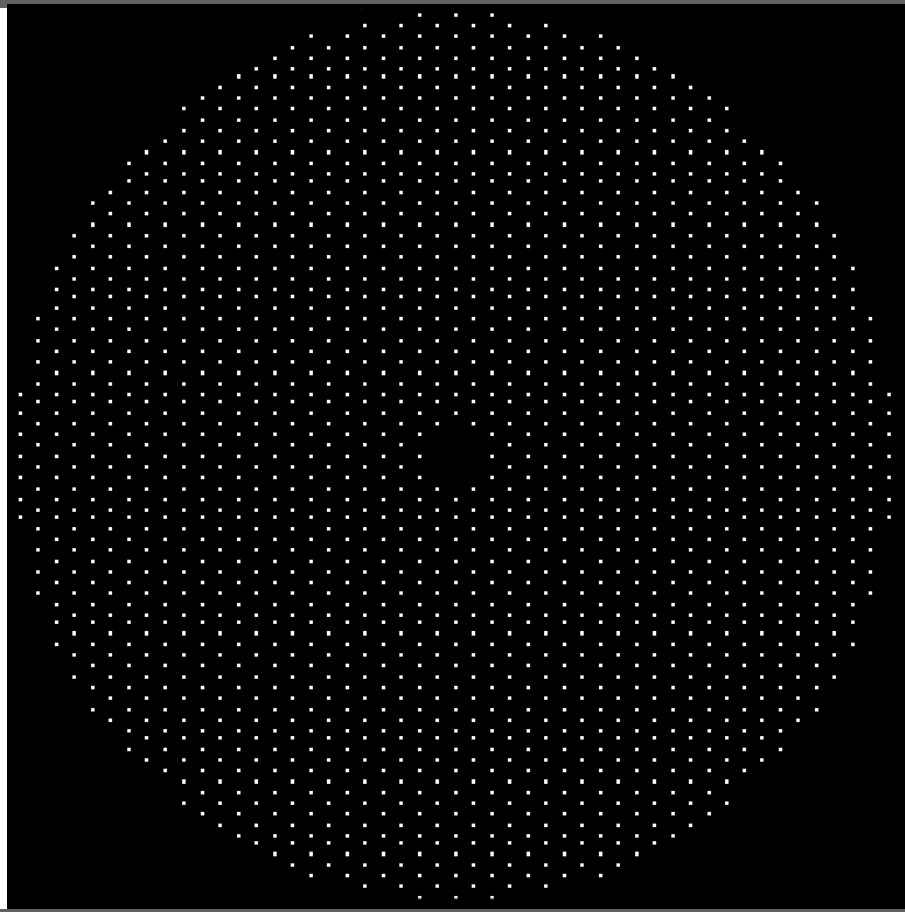


Little, 2017 International Workshop on EUV Lithography (2017)

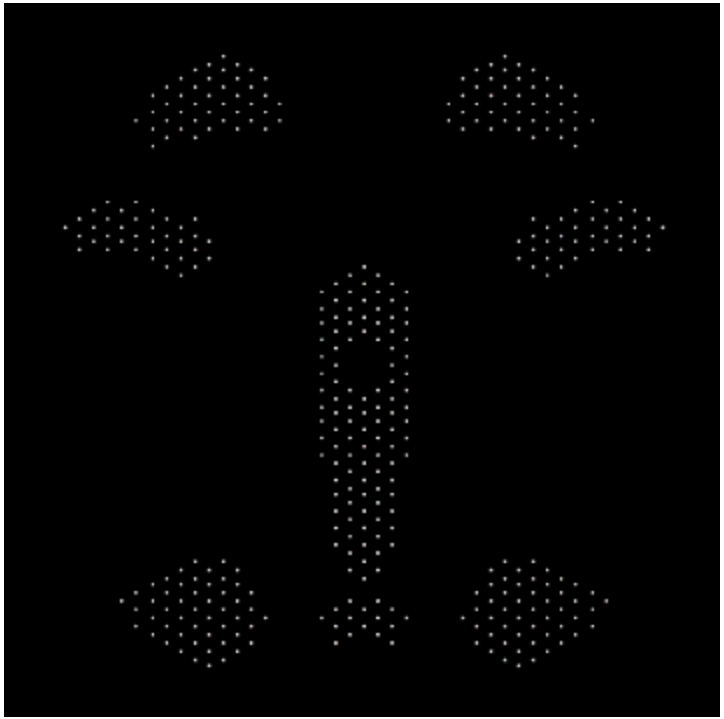
Illuminator Grid

SHARP demonstration:

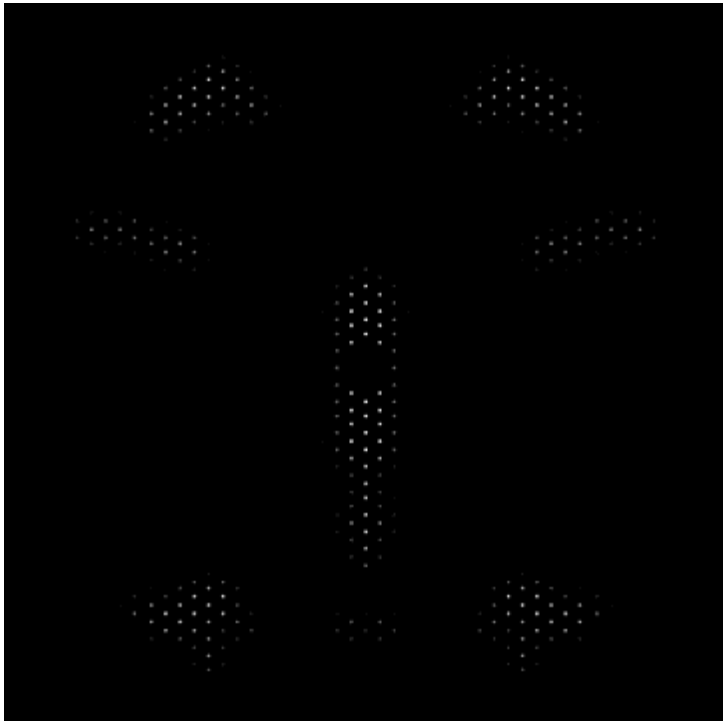
- 1624 pupil channels
- σ from 0.06 to 1.0



Gridded Illuminator

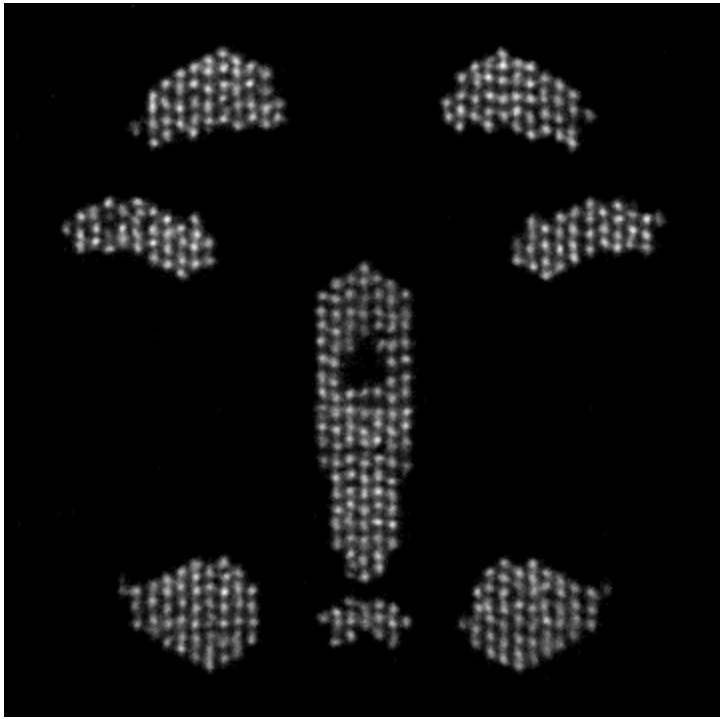


- Binary Source

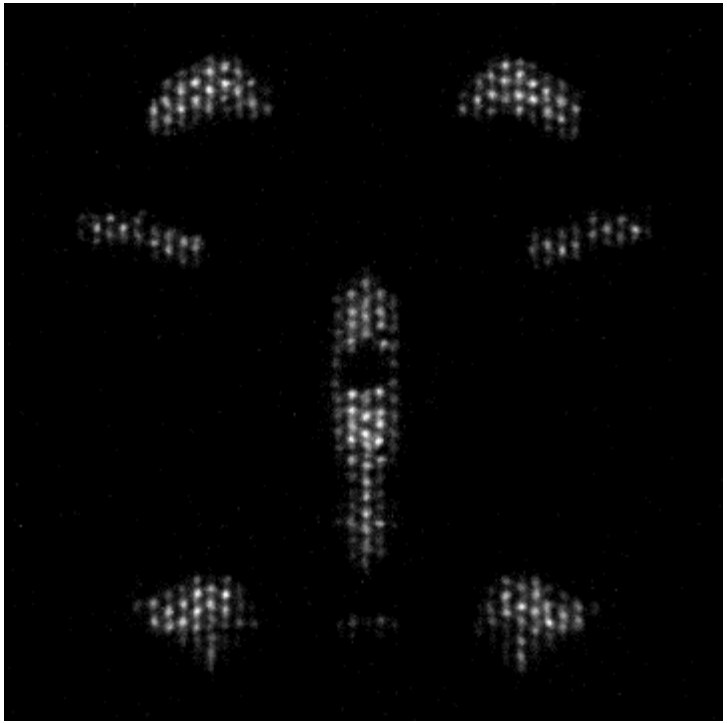


- Modulated Source

SHARP Pupil Fill

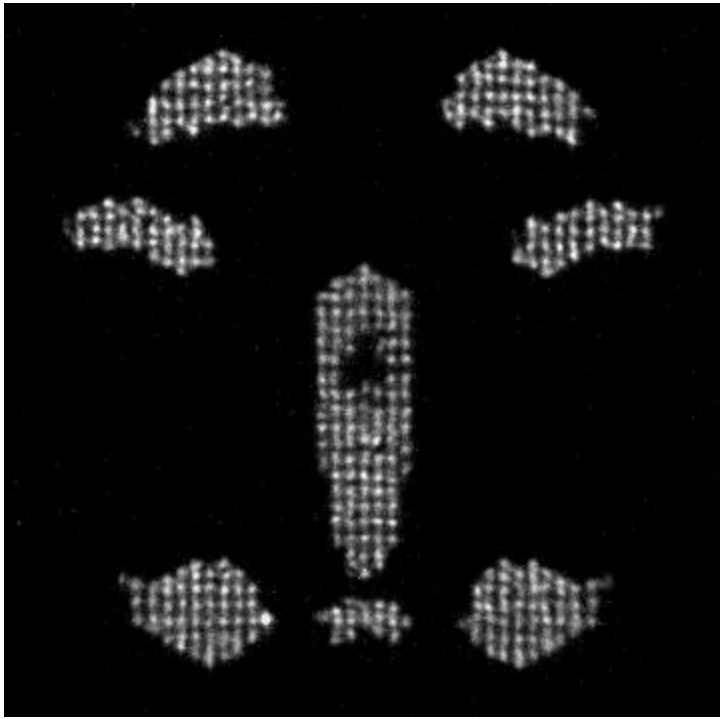


- PFM 2-s loop time

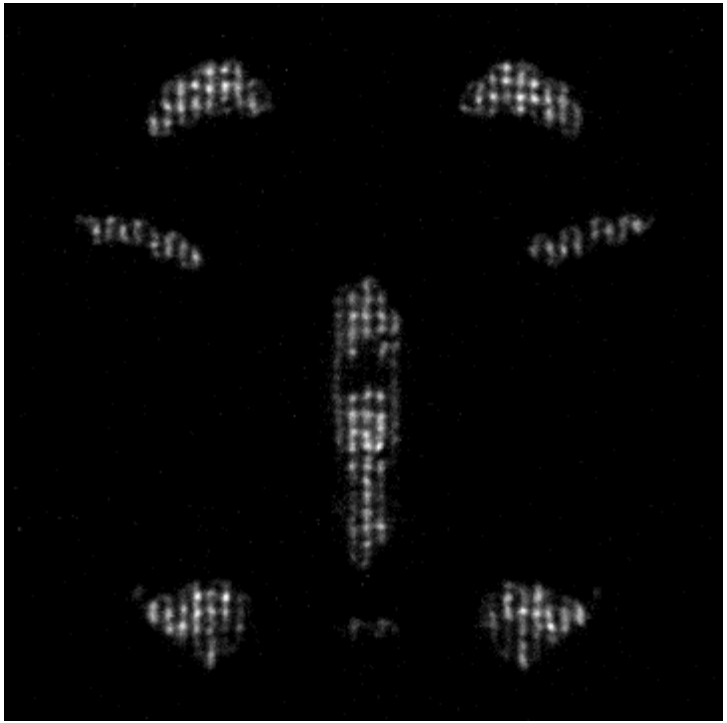


- PFM 2-s loop time

SHARP Pupil Fill

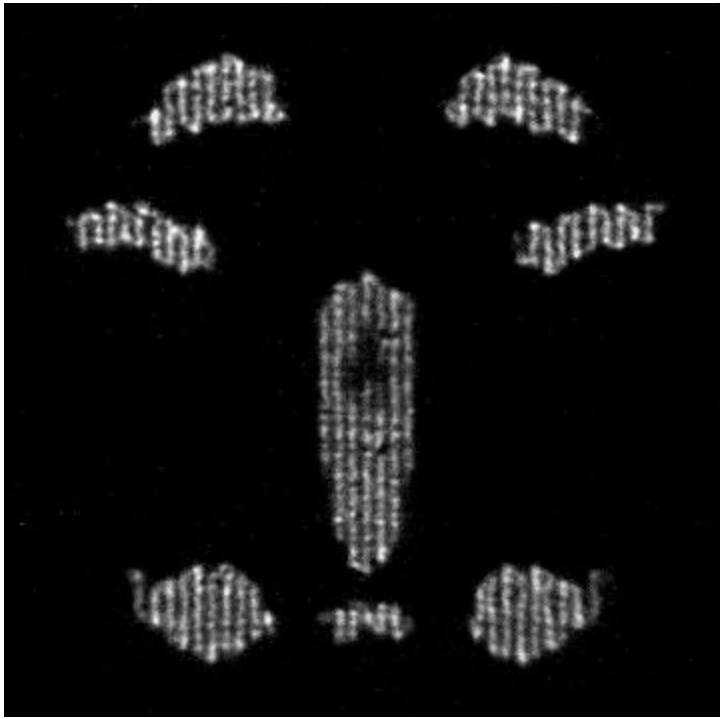


- PFM 1-s loop time

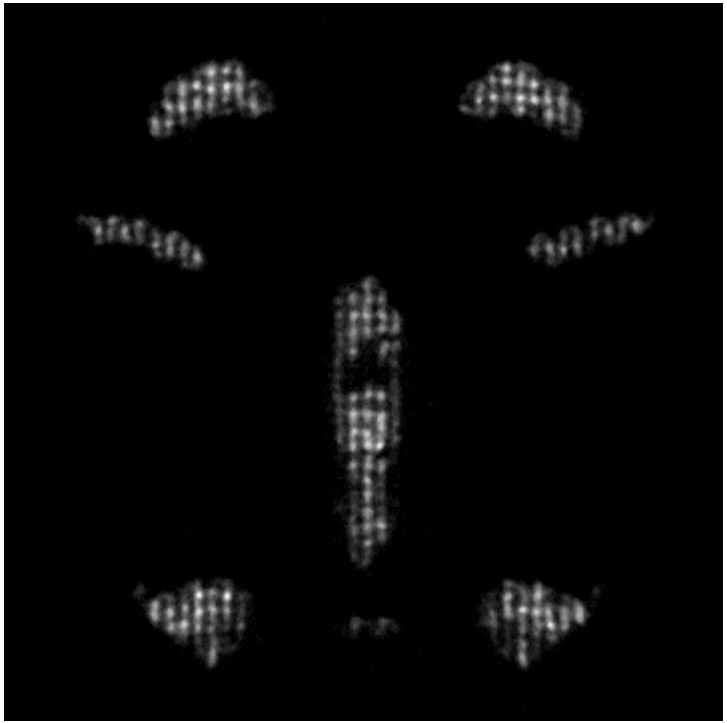


- PFM 1-s loop time

SHARP Pupil Fill

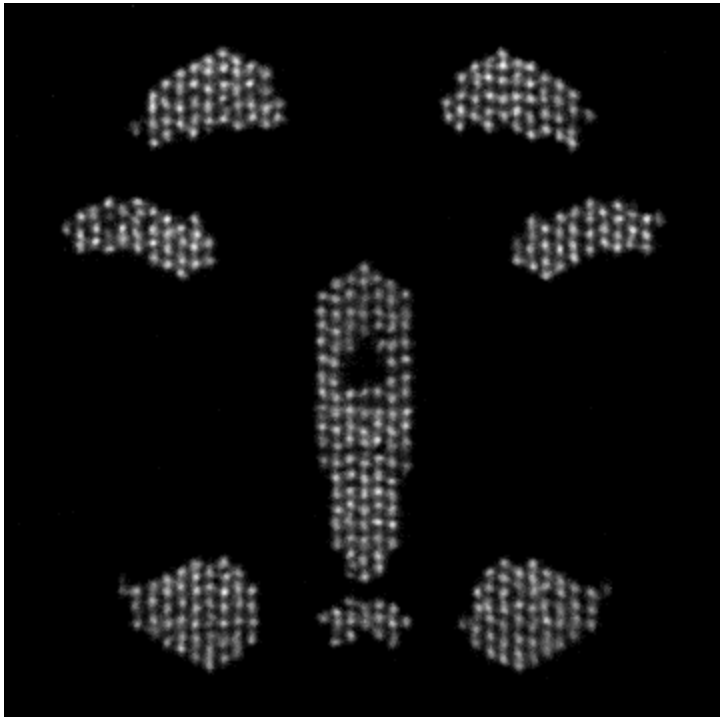


- PFM 0.5-s loop time

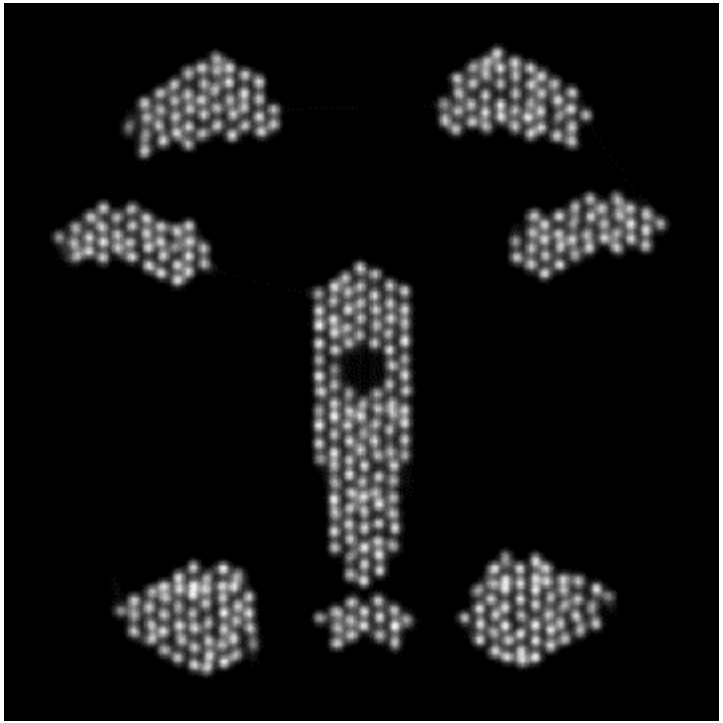


- PFM 0.5-s loop time

Computed Sources

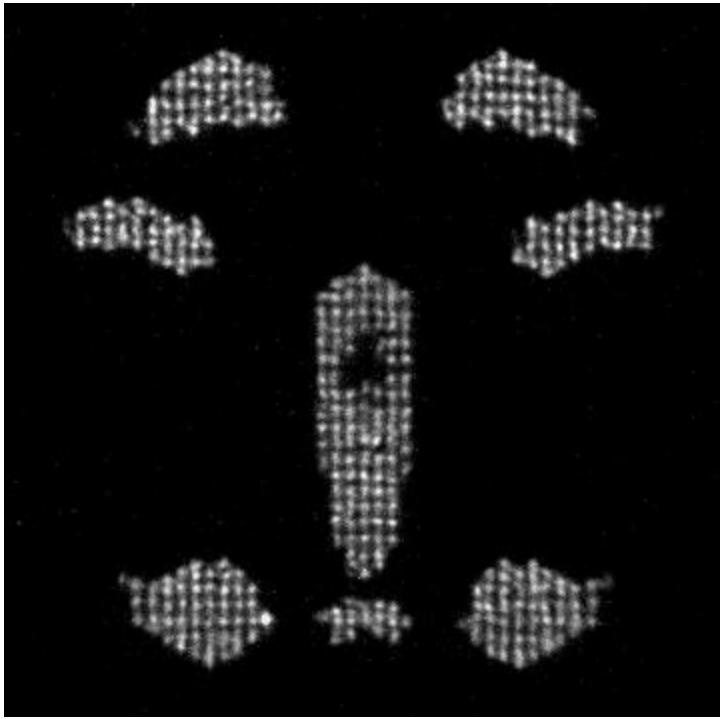


- PFM 2-s loop time

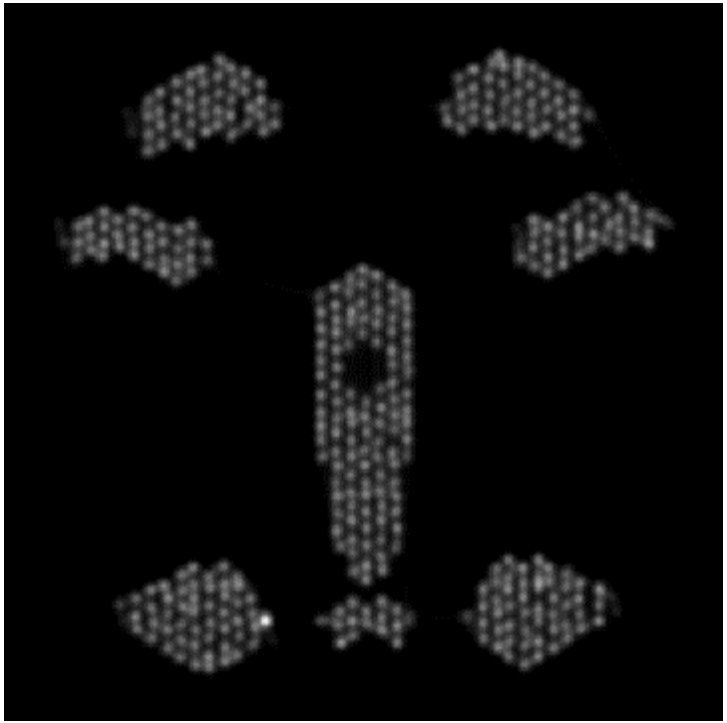


- Modeled source

Computed Sources



- PFM 1-s loop time



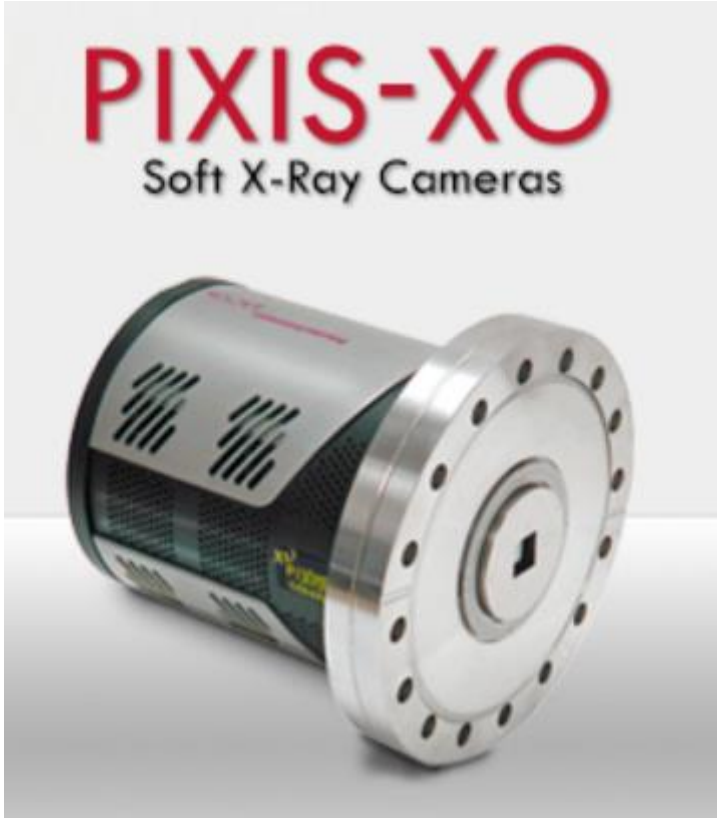
- Modeled source

How much light do you actually need?

Camera upgrade

Current CCD image sensor

- 5-s readout time



Camera upgrade

LBNL detector group builds fast detectors for EUV/SXR.

- CMOS
- 500 frames per second
- virtually no readout time

Flux

SHARP image:

- 50k cts/pixel (full well exposure)

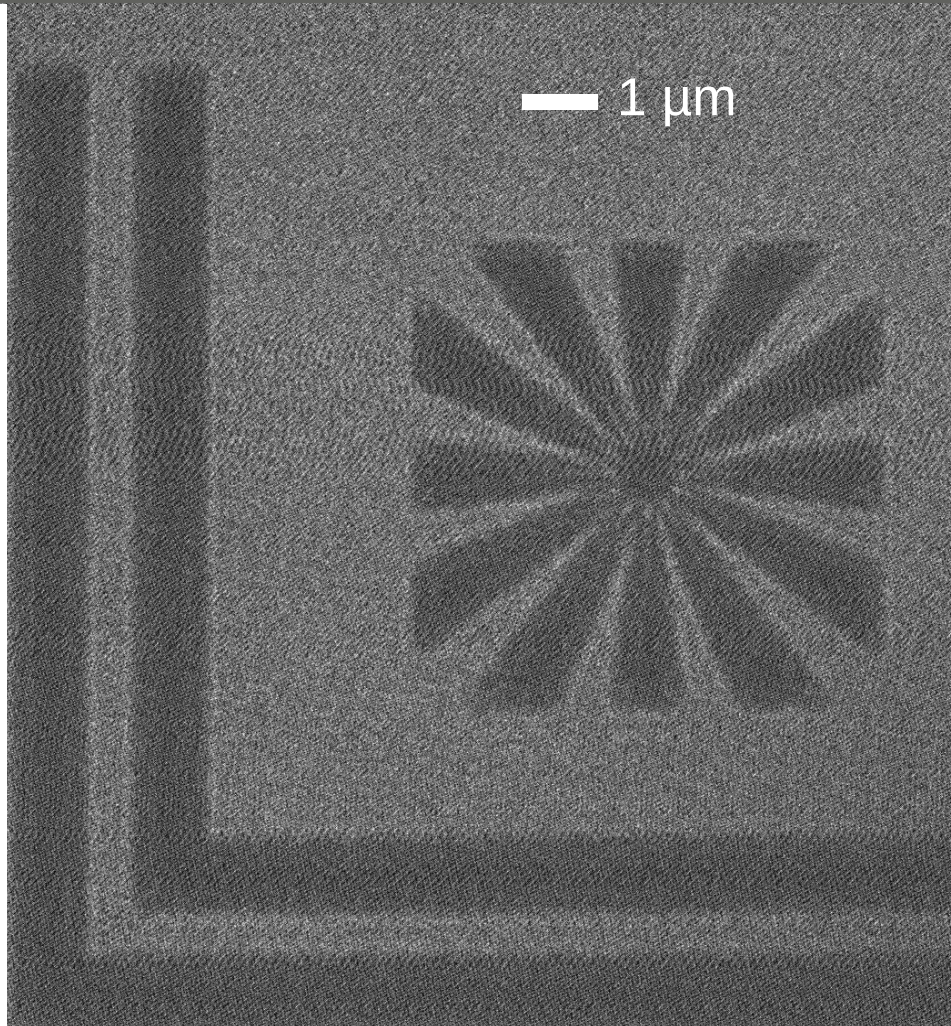
~10k photons / pixel @ 5 cts/photon

- 2000 photons/(s pixel) @ T=5s

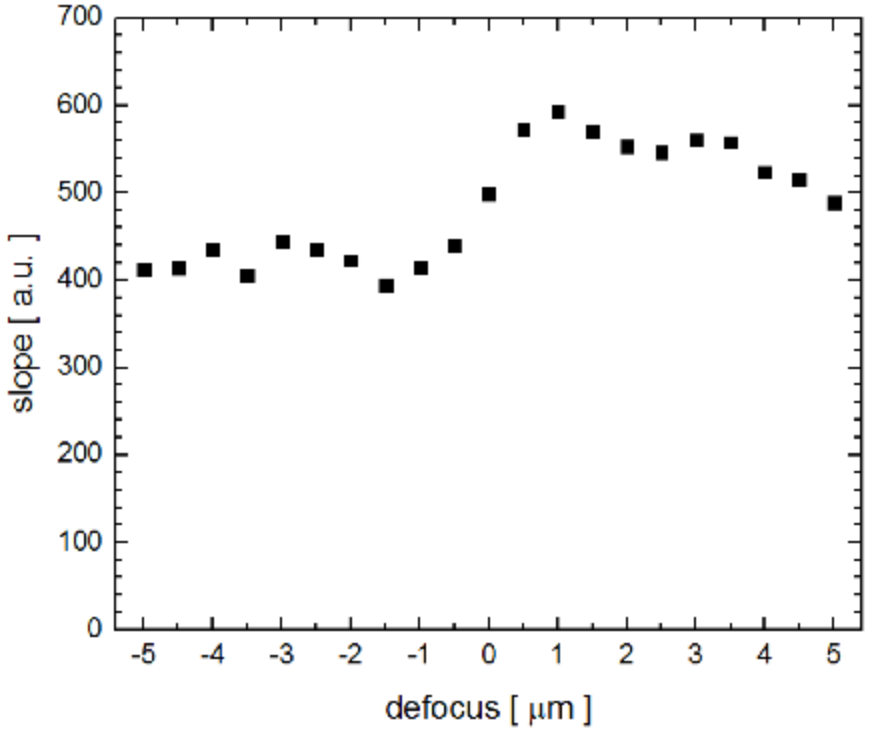
~4 photons/(frame pixel) @ 500 Hz

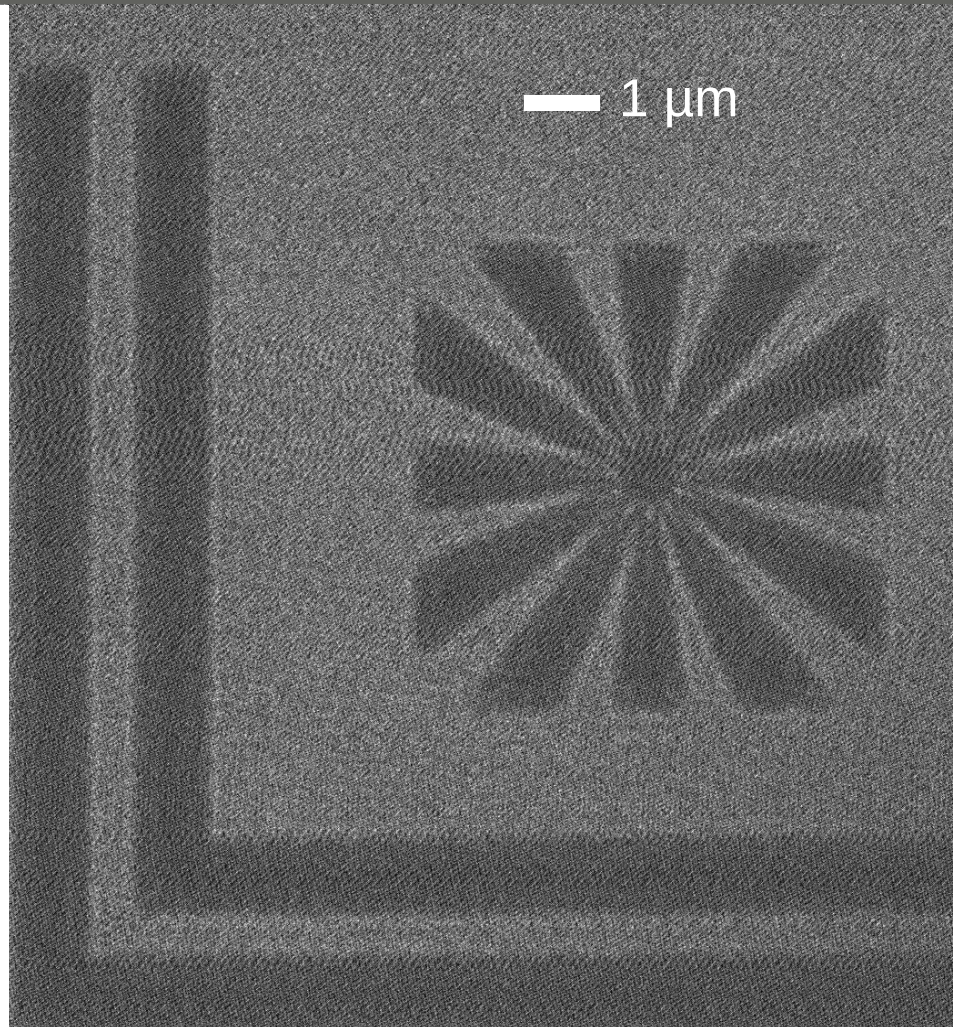
~40 photons/(frame pixel) @ 50 Hz

- 5 photons / pixel



Autofocus


700
600
500
400
300
200
100
0
slope [a.u.]
-5
-4
-3
-2
-1
0
1
2
3
4
5
defocus [µm]

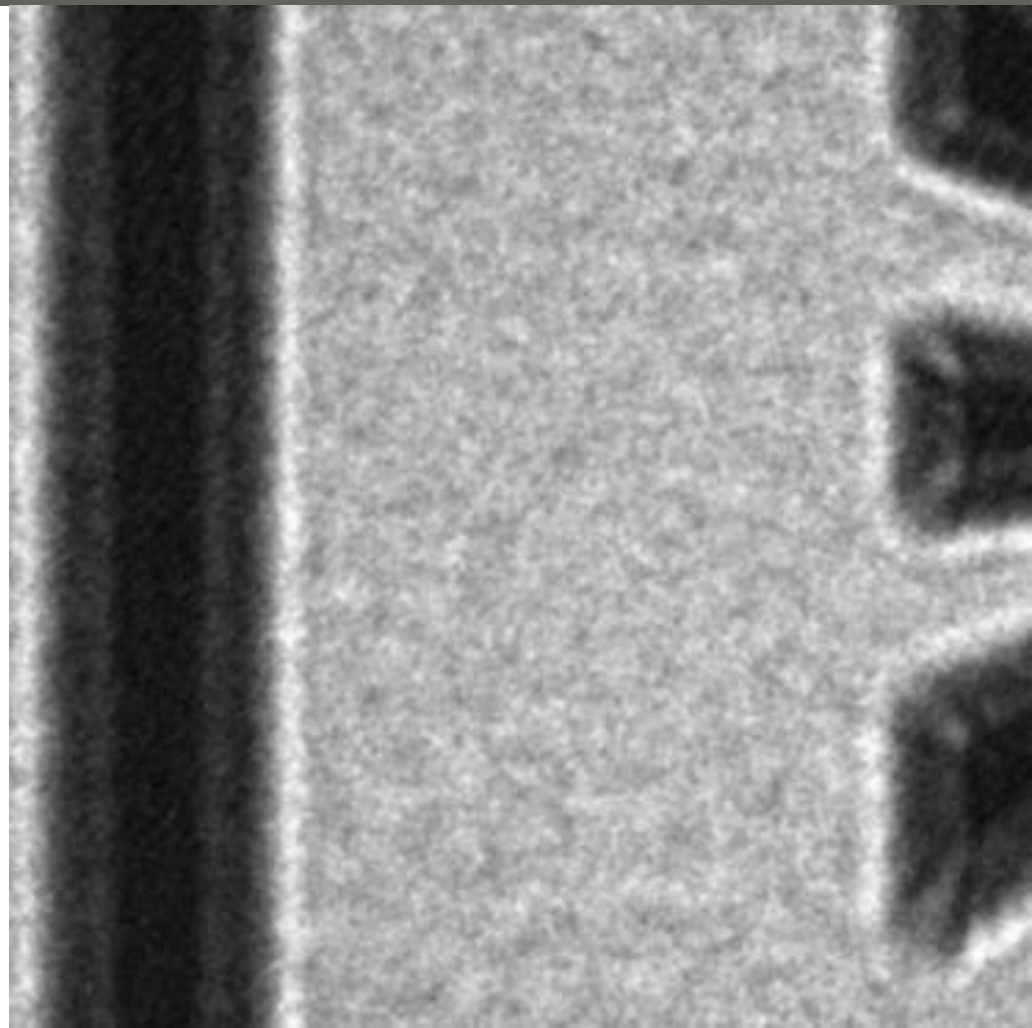

1 µm

Autofocus

1 µm

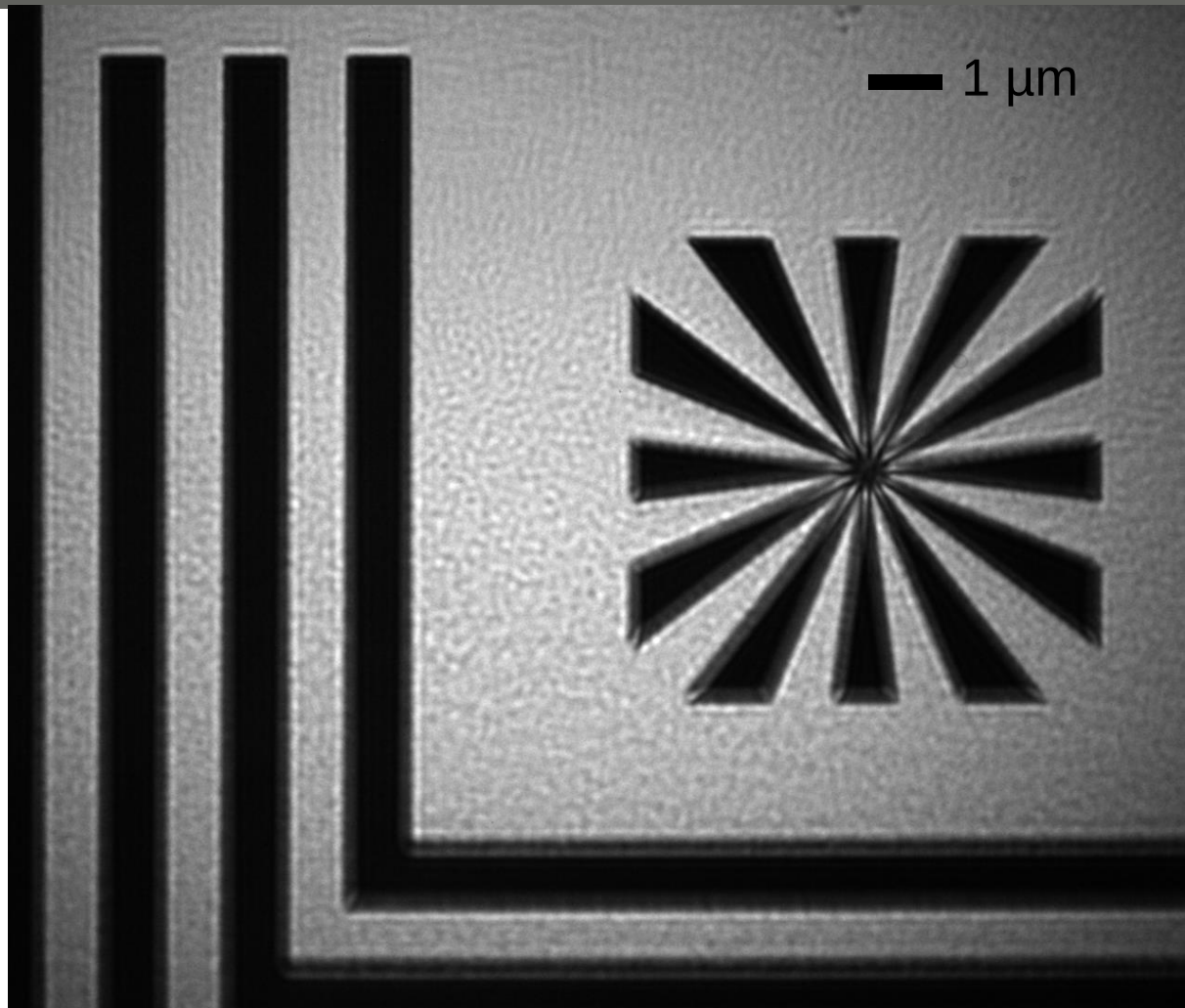
- 80 photons / pixel

~25 Hz

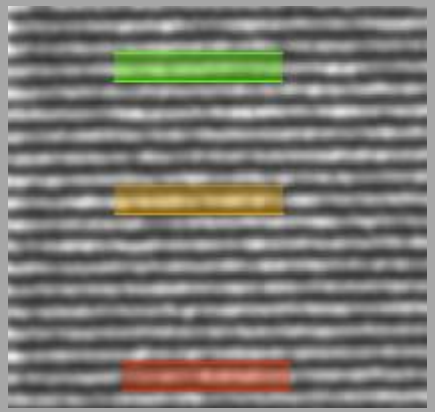


Tilted focal plane

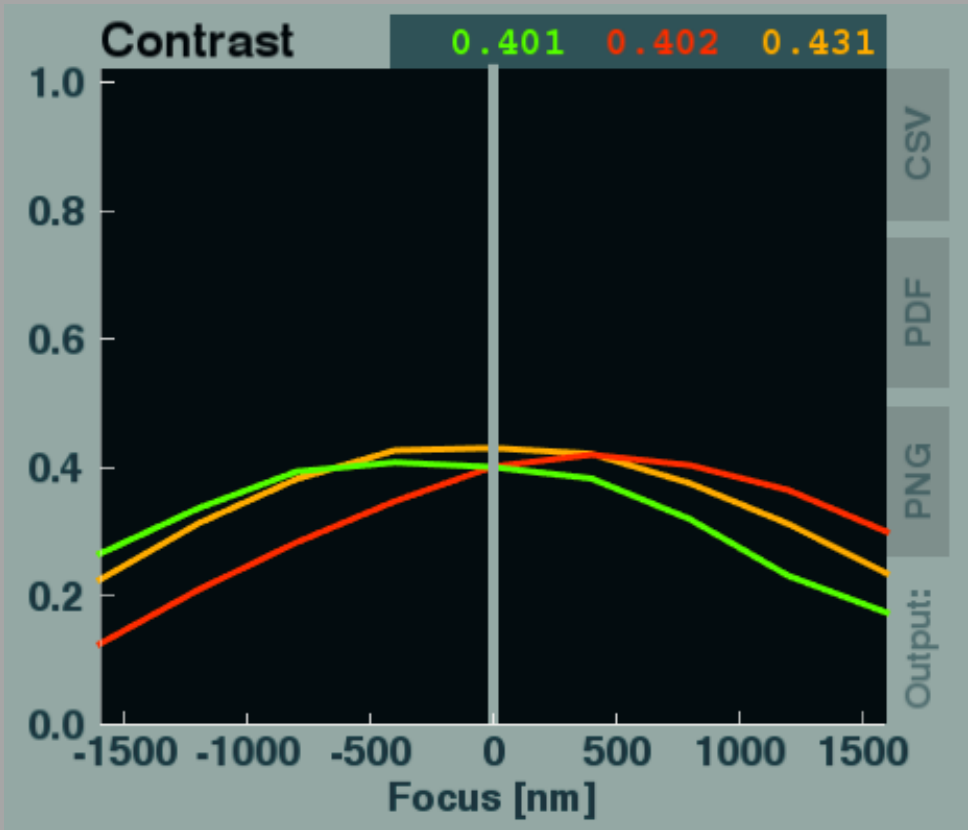
- 2-µm steps trough focus



Tilted focal plane



1 µm



Continuous focus stack

Continuous focus stack

Center on best focus

Continuous focus stack

Arbitrary step size

Center on best focus

Continuous focus stack

Arbitrary step size

Center on best focus

Exposure time

Continuous focus stack

Correct tilted plane

Arbitrary step size

Center on best focus

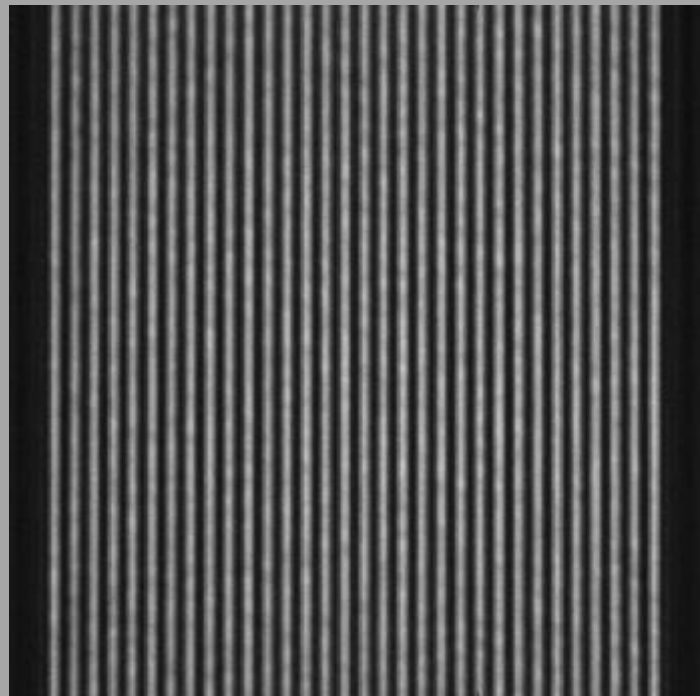
Exposure time

Continuous focus stack

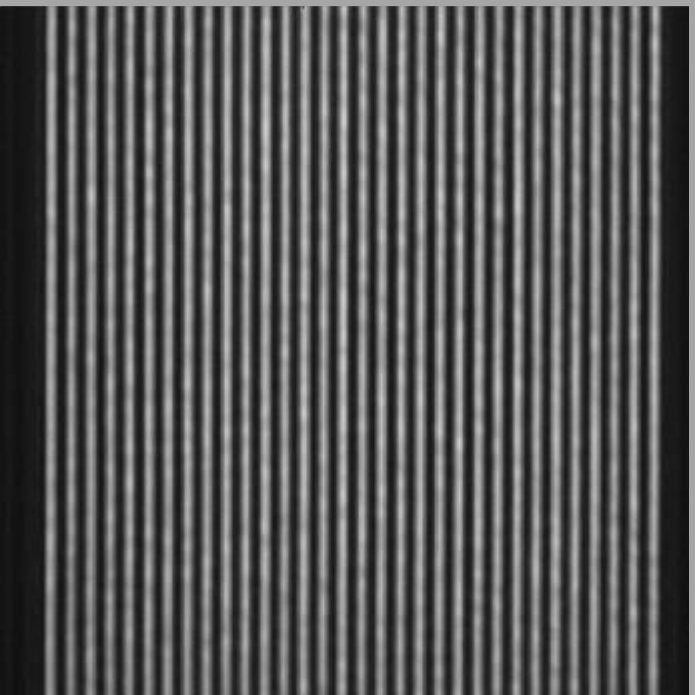
Regular series: $\Delta z = 400\,\text{nm}$

Current minimum step size:
$\Delta z = 50\,\text{nm}$

Tilted focal plane:
$\Delta z = 50\,\text{nm}$ / 15 lines (image)



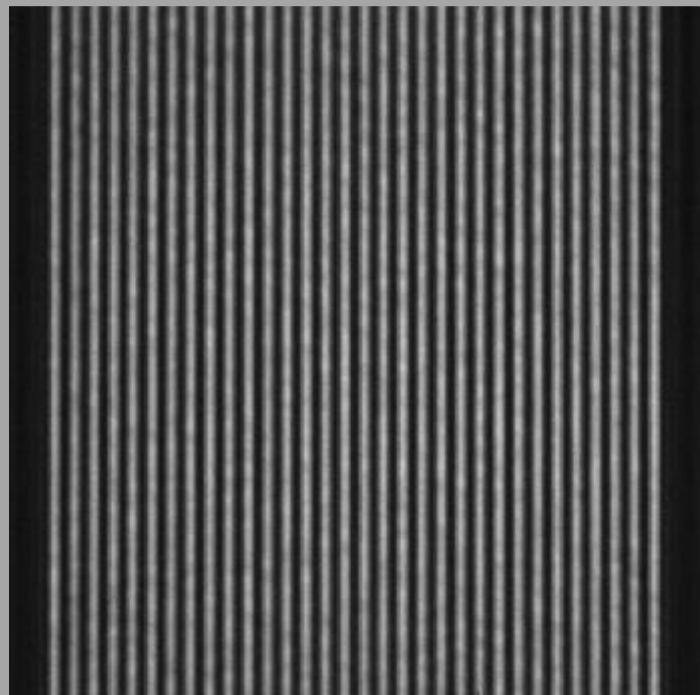
#	1	8	28	56	70	56	28	8	1
z [nm]	-200	-150	-100	-50	0	50	100	150	200



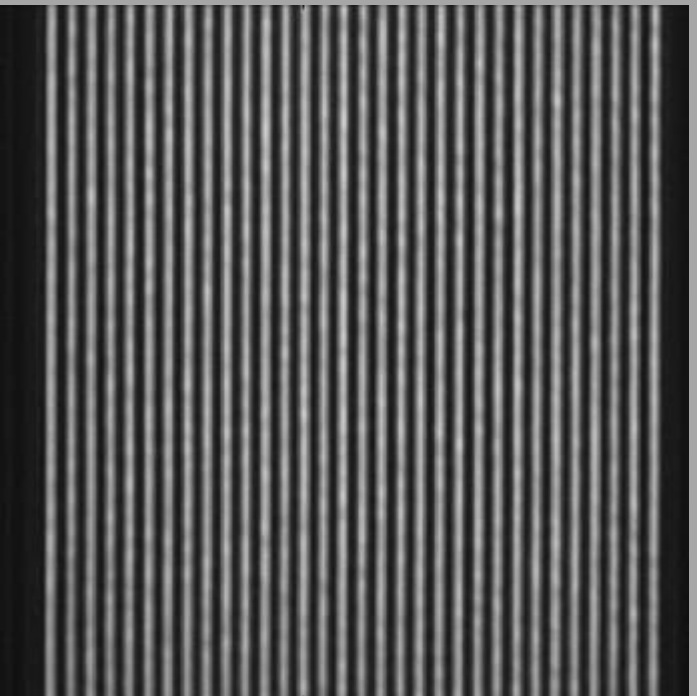
composite

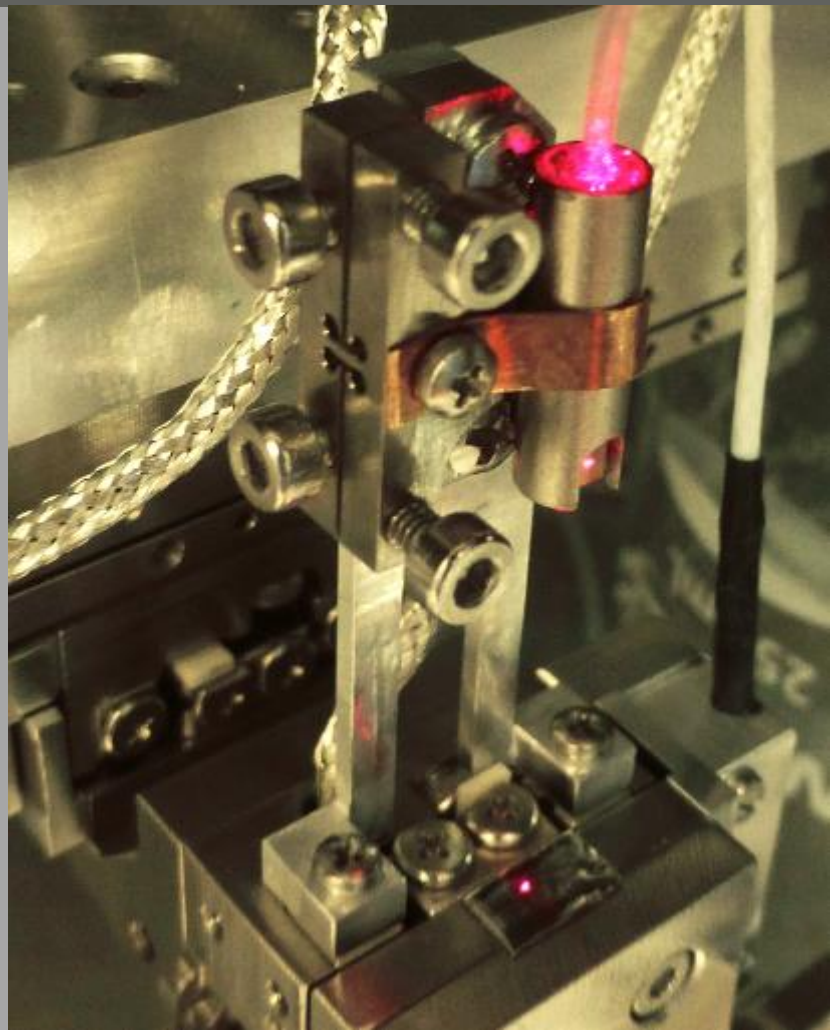
1 µm

regular

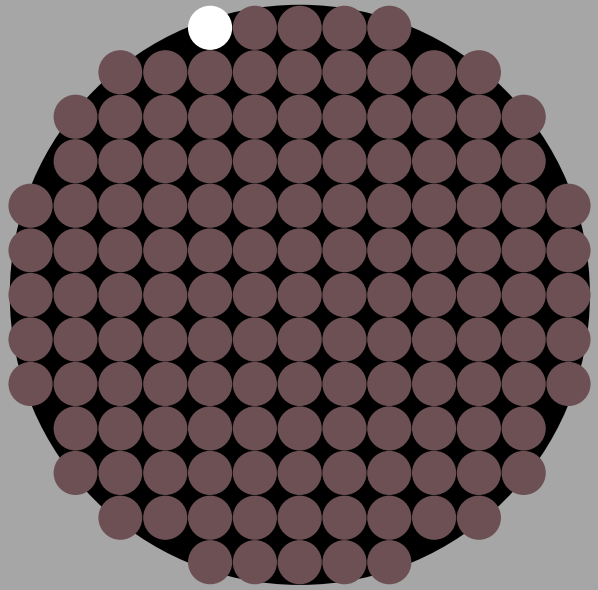


ZP interferometer



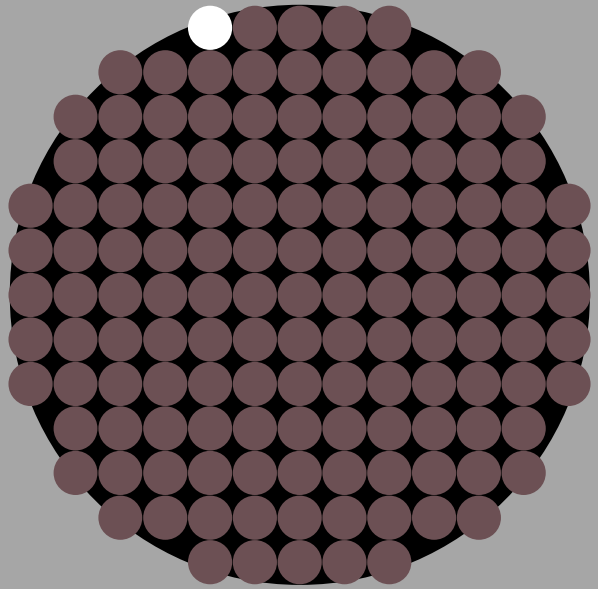


Source Optimization

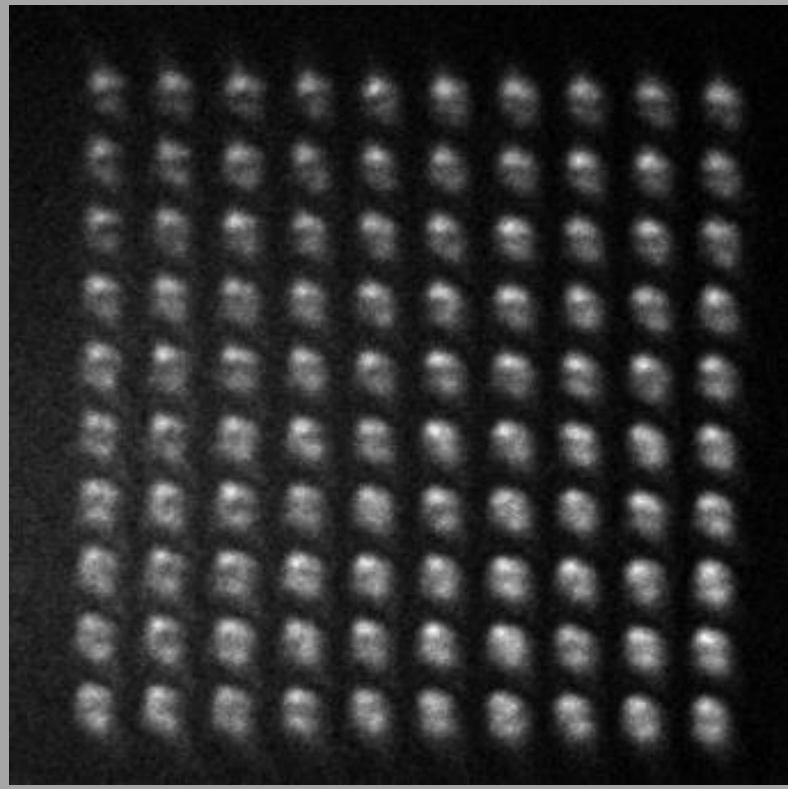


- Pupil Channel
  α

Source Optimization

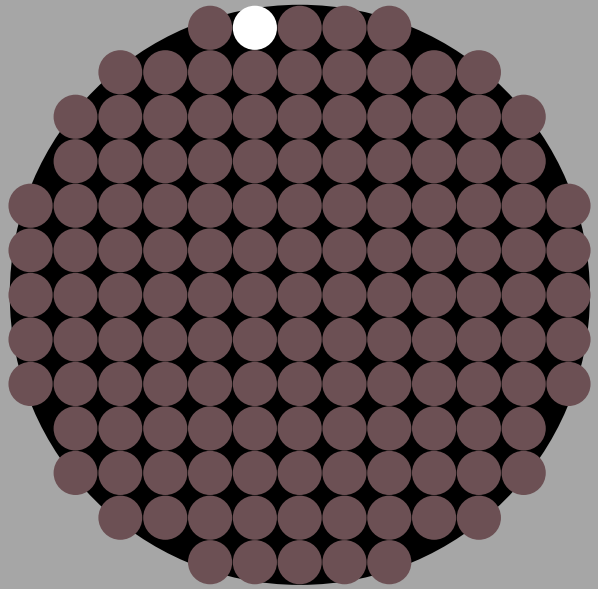


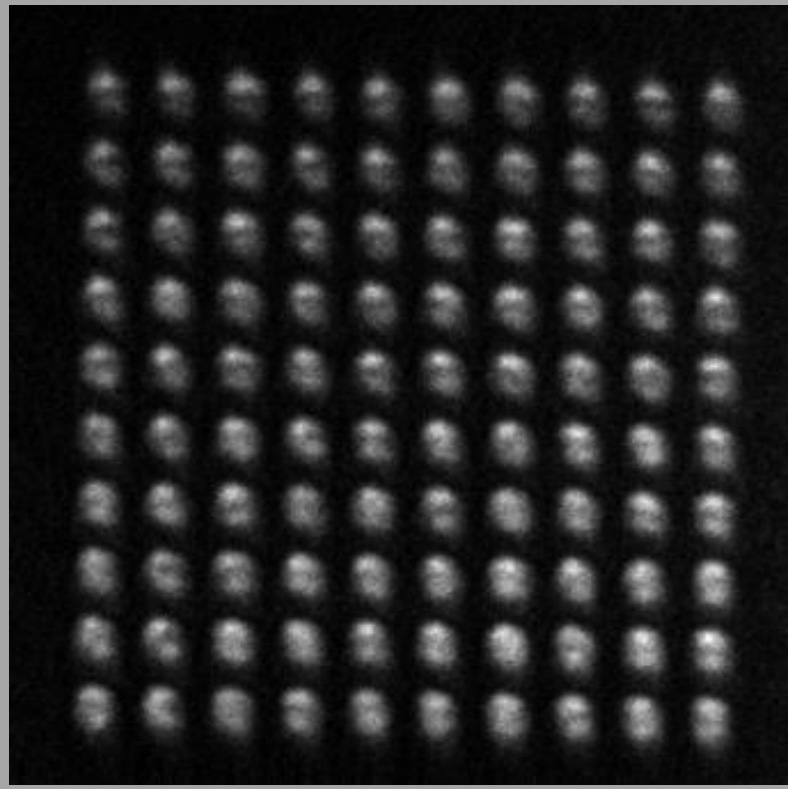
- Pupil Channel α



- Image i_a

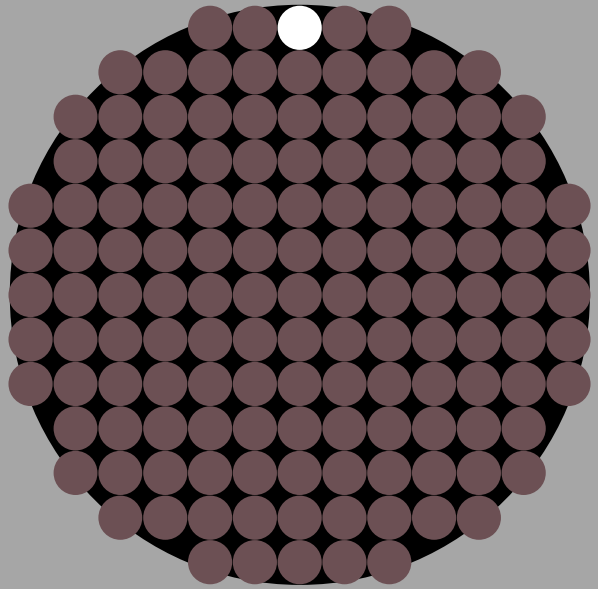
Source Optimization



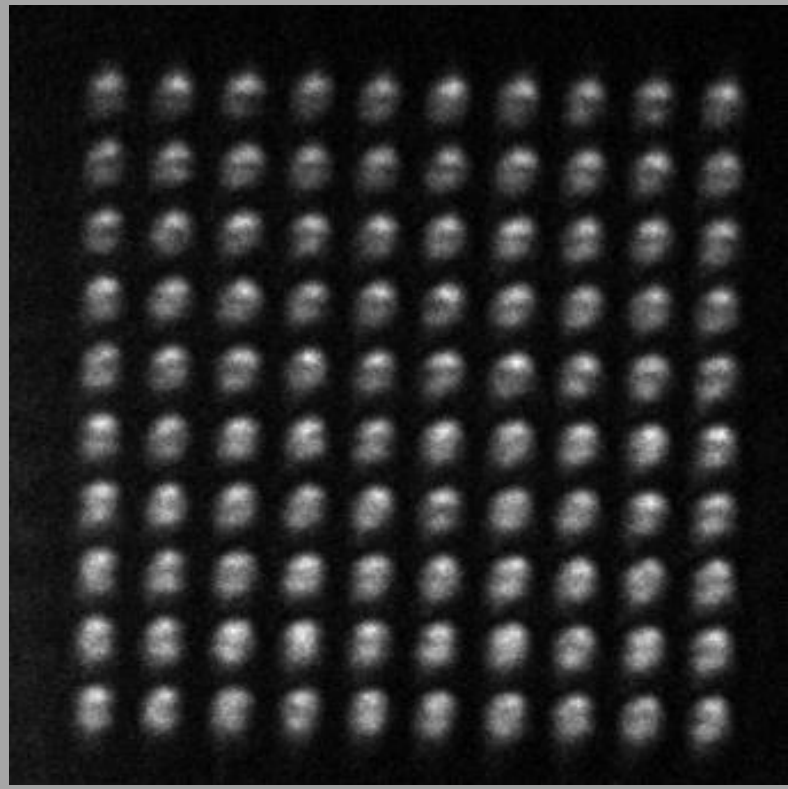


- Pupil Channel
  α

Source Optimization

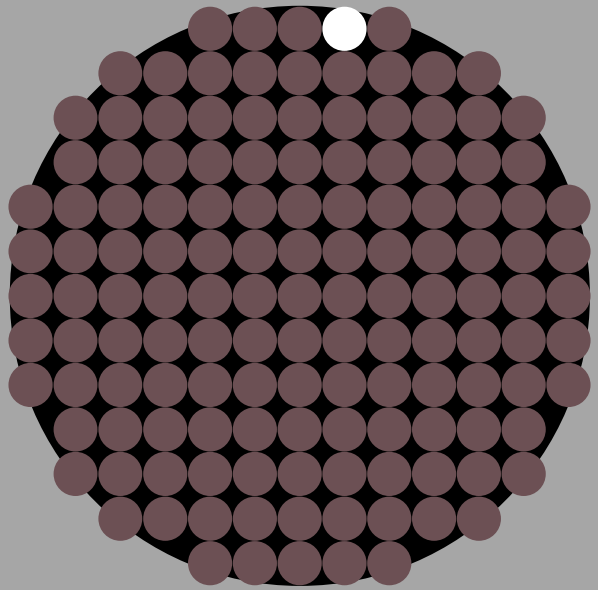


- Pupil Channel α

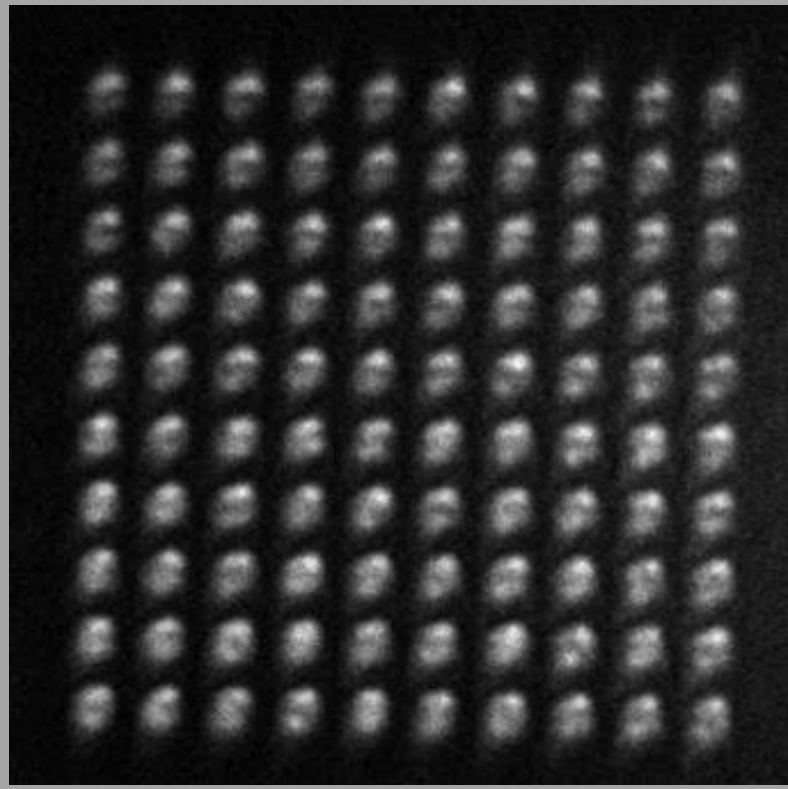


- Image i_a

Source Optimization

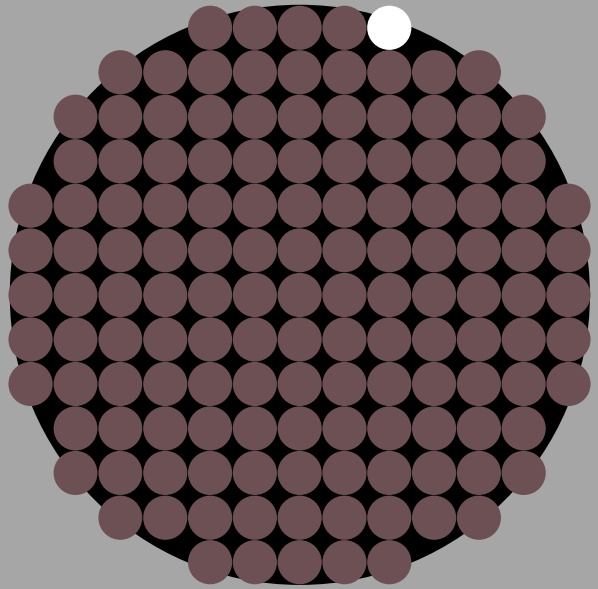


- Pupil Channel α

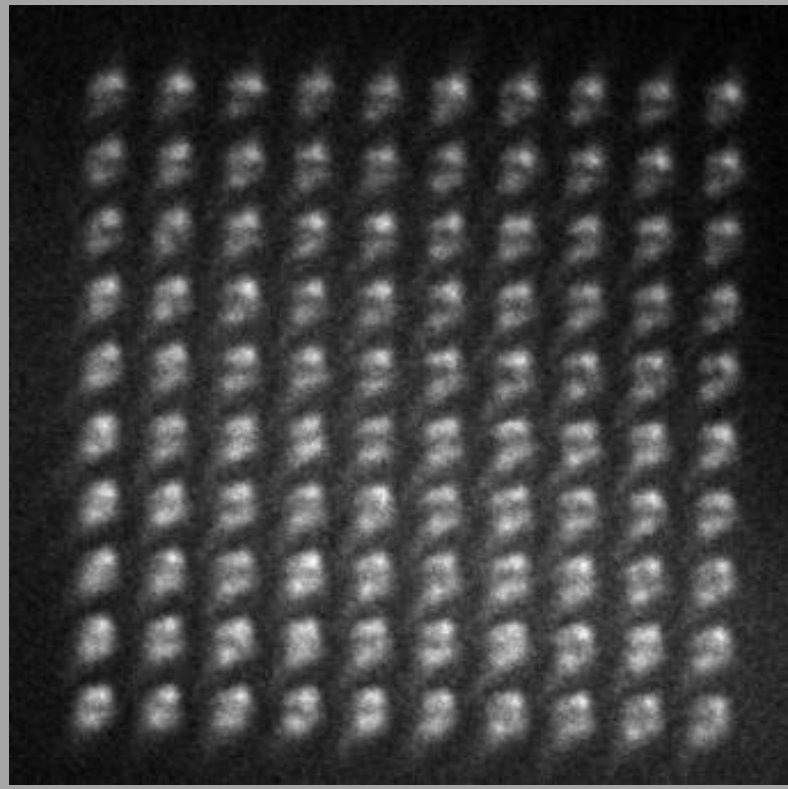


- Image i_a

Source Optimization

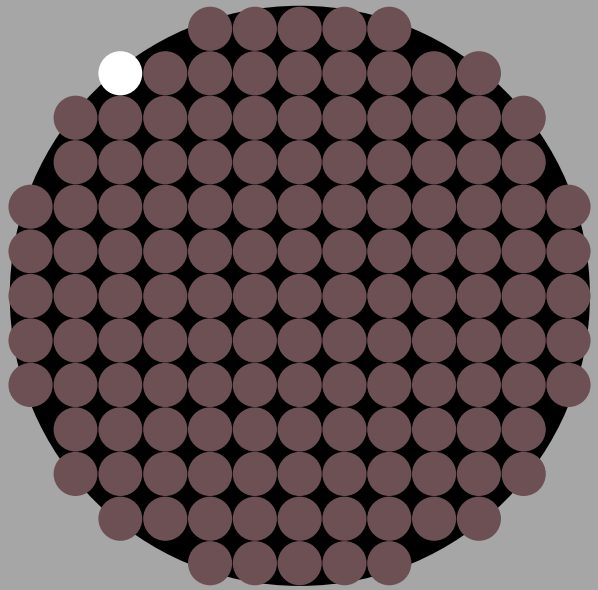


- Pupil Channel α

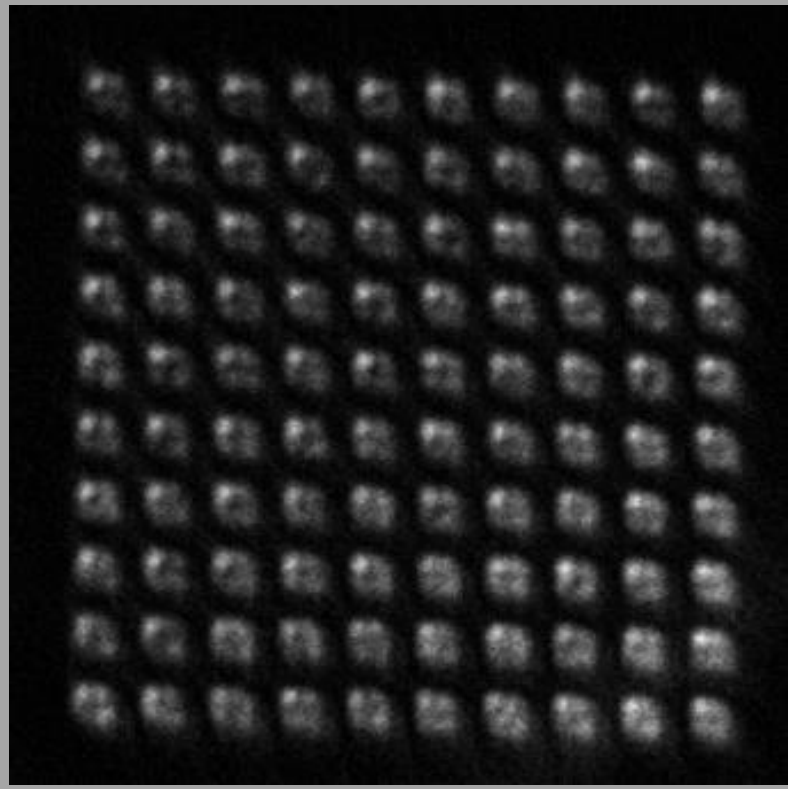


- Image i_a

Source Optimization

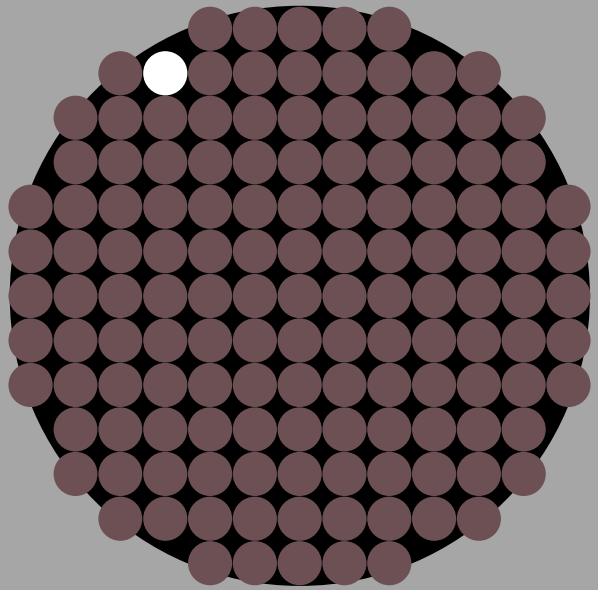


- Pupil Channel α

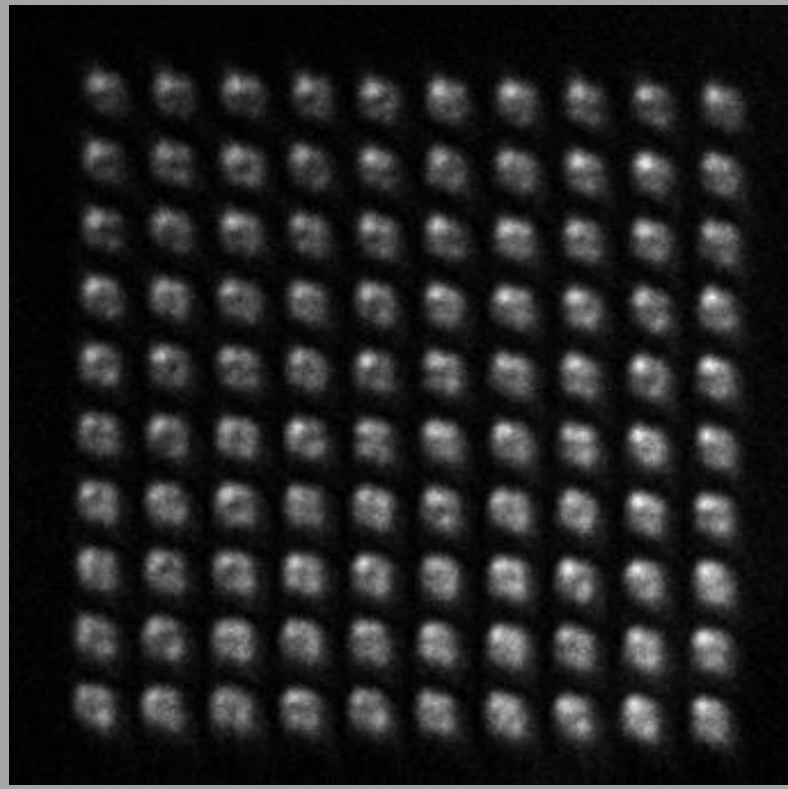


- Image i_a

Source Optimization

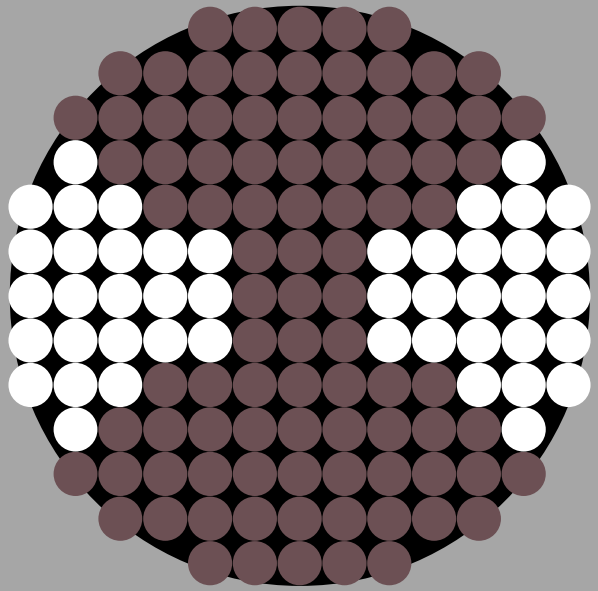


- Pupil Channel α



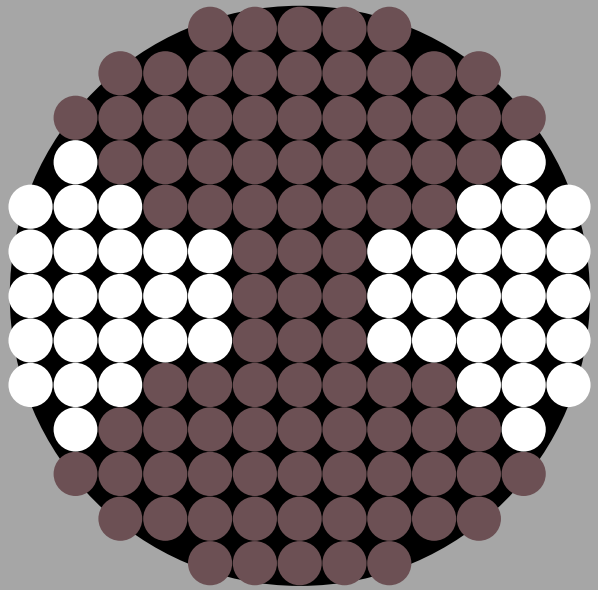
- Image i_a

Source Optimization

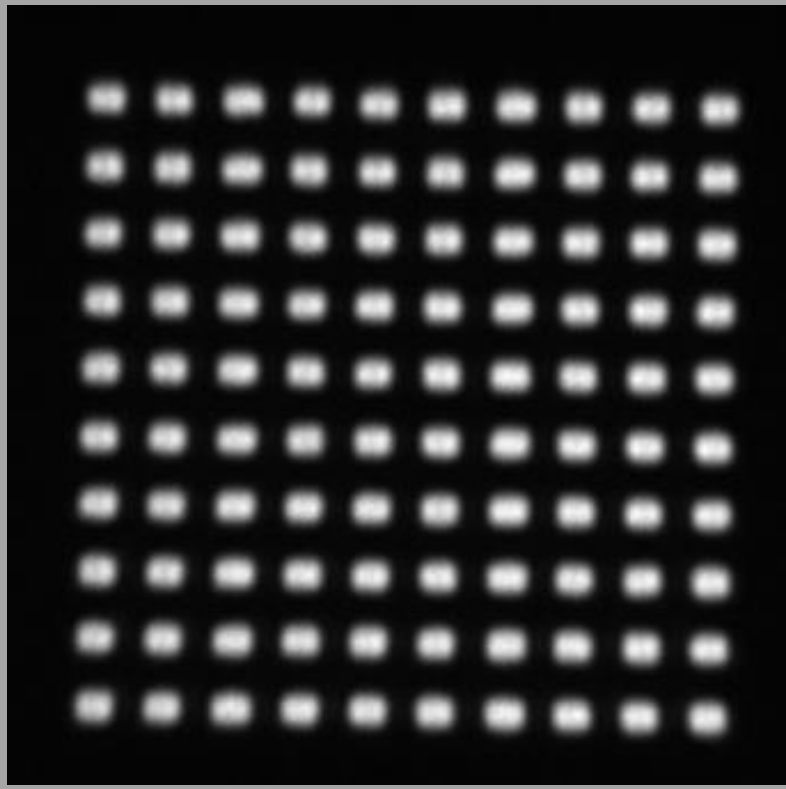


- Pupil

Source Optimization

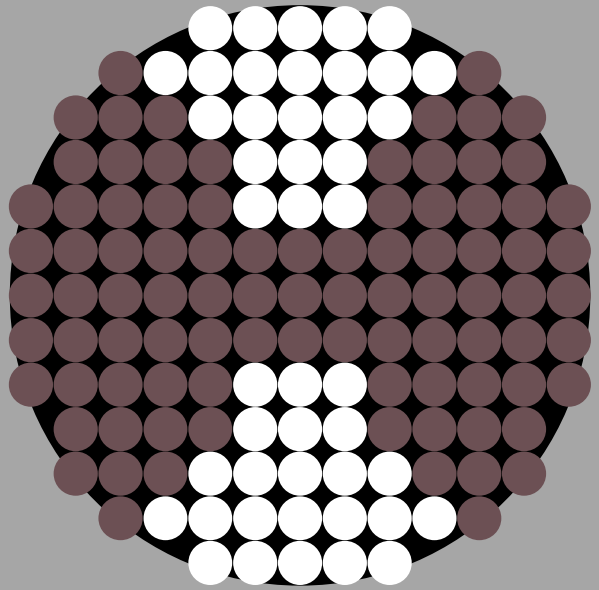


- Pupil

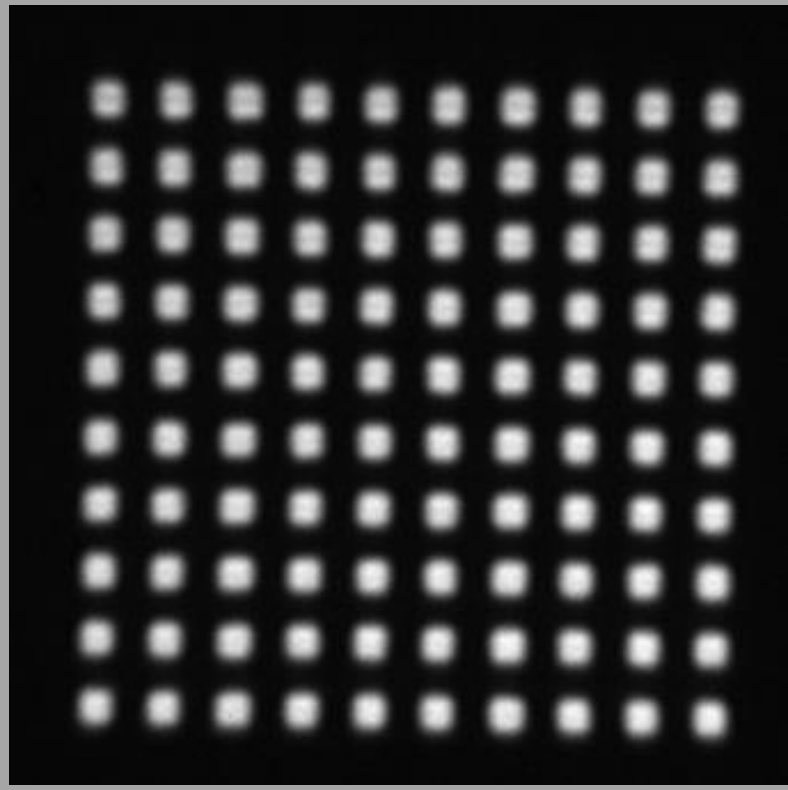


- Image $I = \sum_a i_a$

Source Optimization

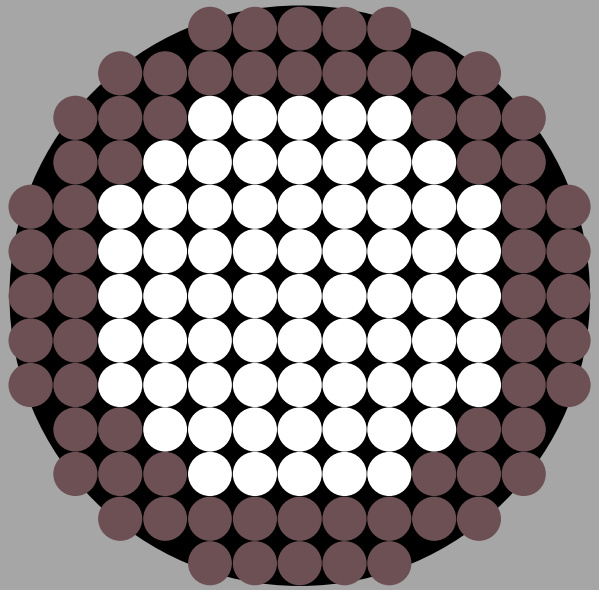


- Pupil

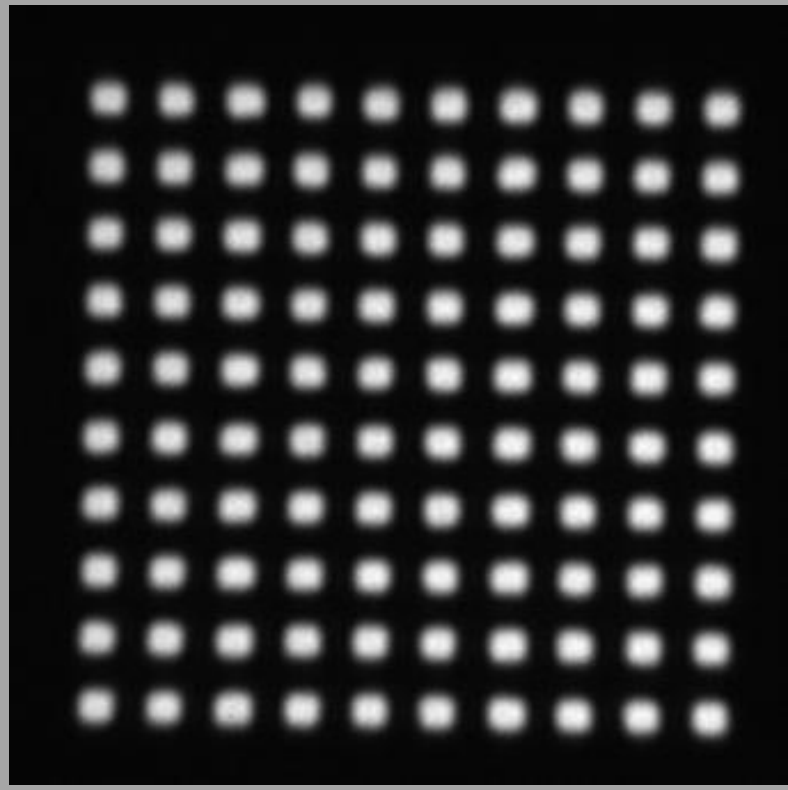


- Image $I = \sum_a i_a$

Source Optimization



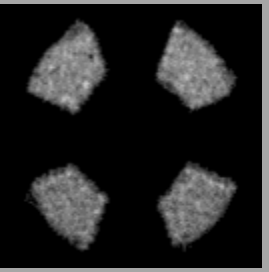
- Pupil

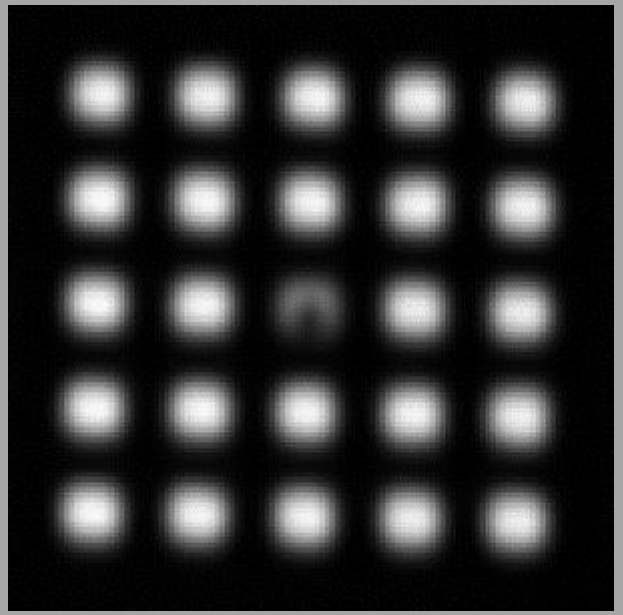


- Image $I = \sum_a i_a$

Source Optimization

- Quasar

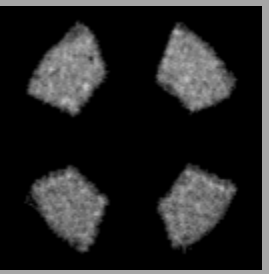


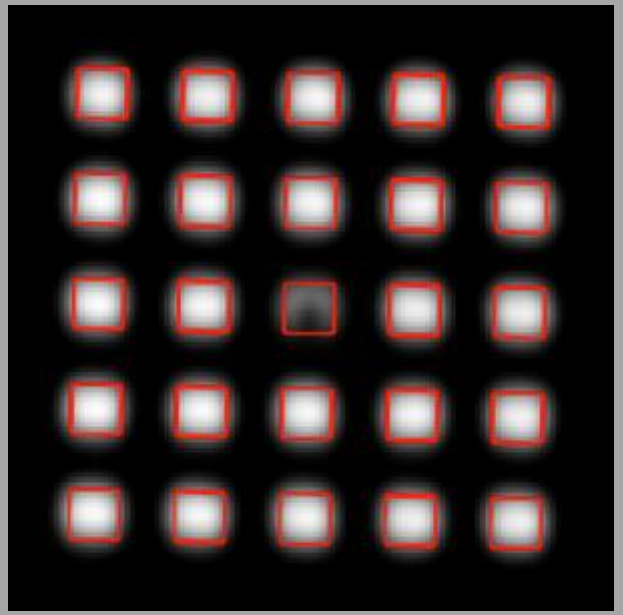


- 40-nm (1x) dense contacts

Source Optimization

- Quasar

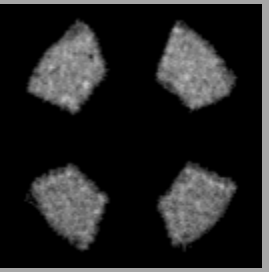


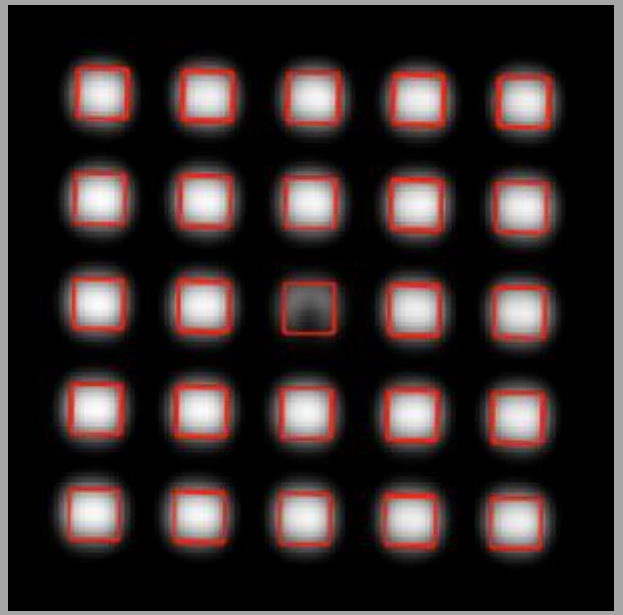


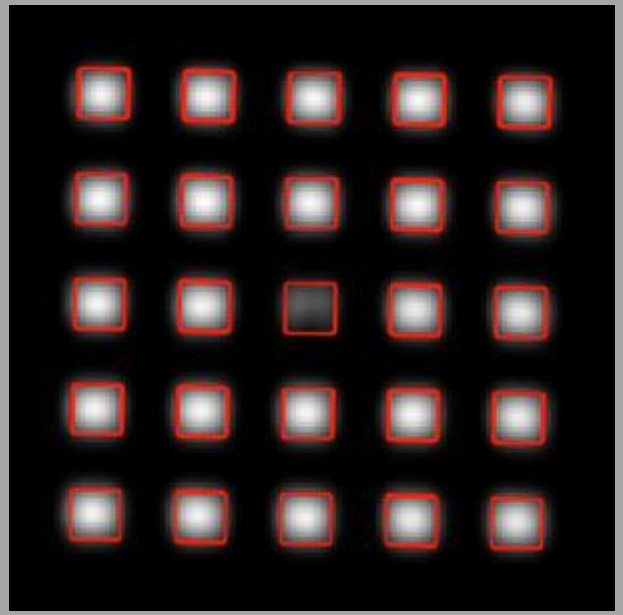
- 40-nm (1x) dense contacts

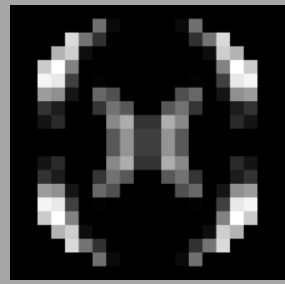
Source Optimization

- Quasar
- Freeform Source









- 40-nm (1x) dense contacts

Source Optimization

- Quasar
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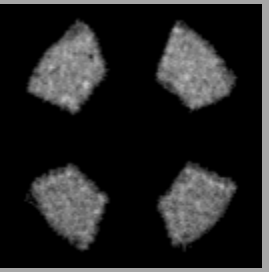
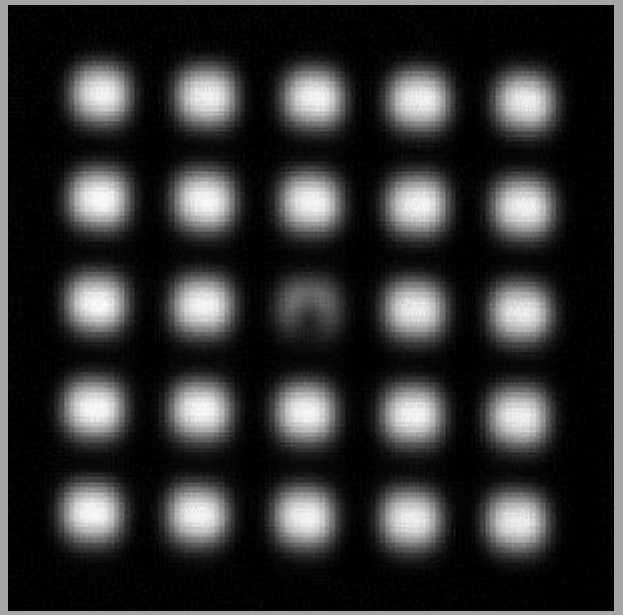
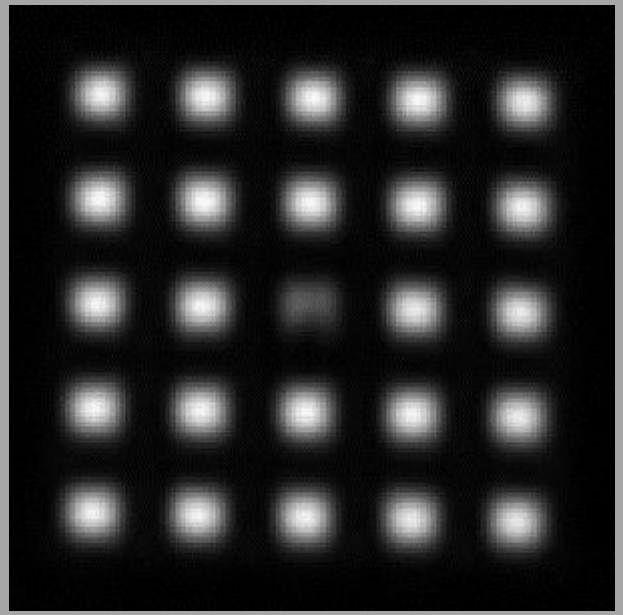
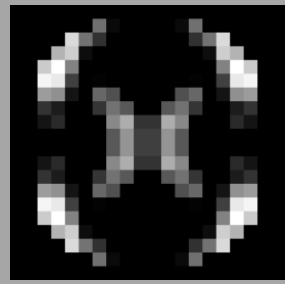


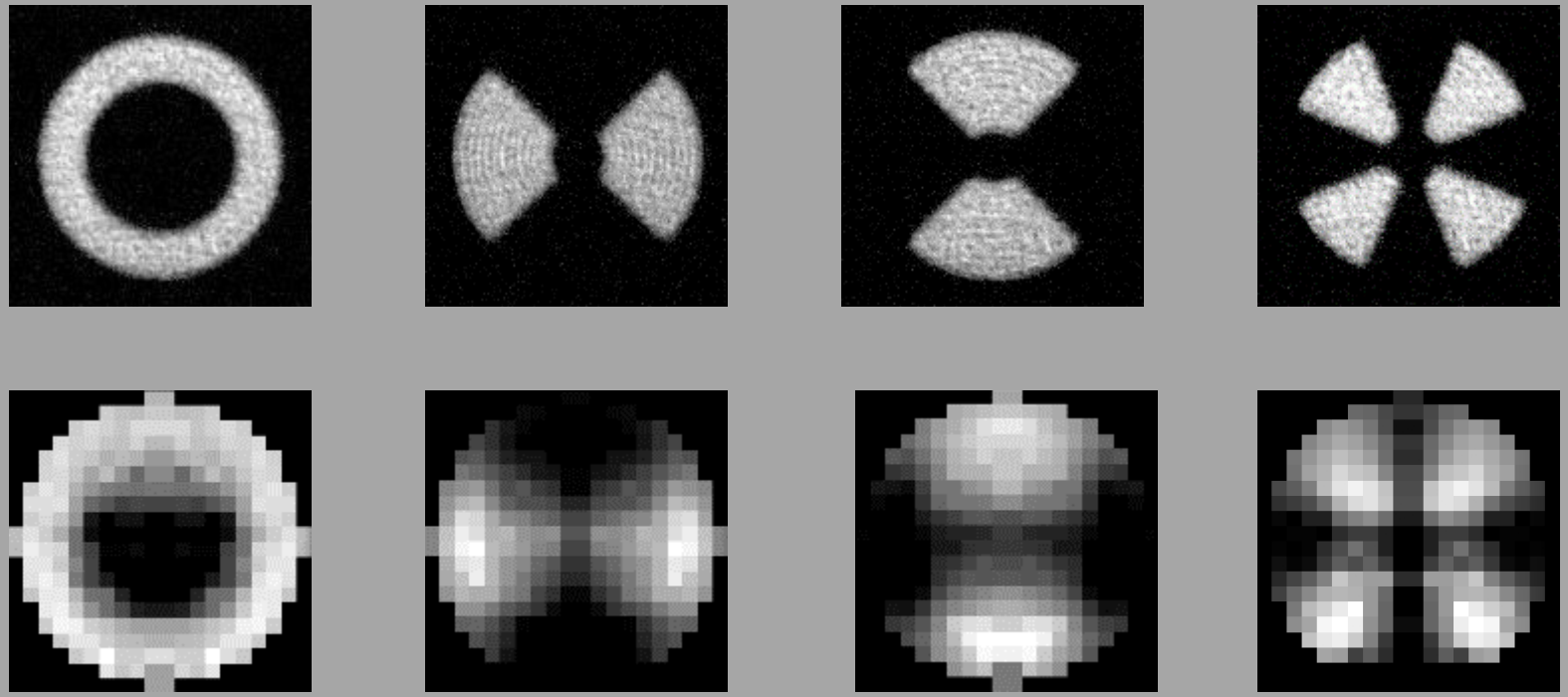






- 40-nm (1x) dense contacts

Reconstruction of pupil fill from image



Source Optimization

Limitations:

- 30+ min acquisition time
- Number of sources
- No through-focus capability
- Image drift

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Upgraded sensor with high frame rate:

- full source angular spectrum in 10s total exposure time
- Shot noise identical to regular SHARP data
- Through-focus capability
- Virtually no image drift

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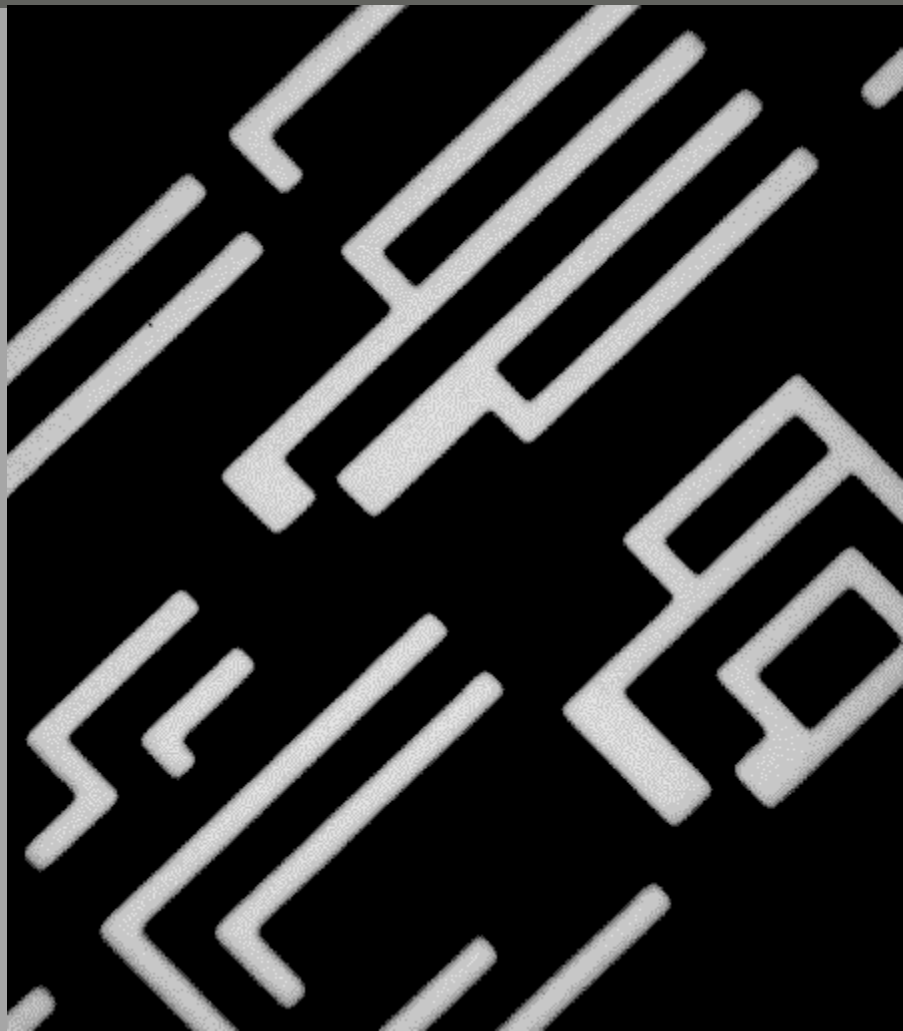
Summary

SHARP High-NA Actinic Reticle Review Project

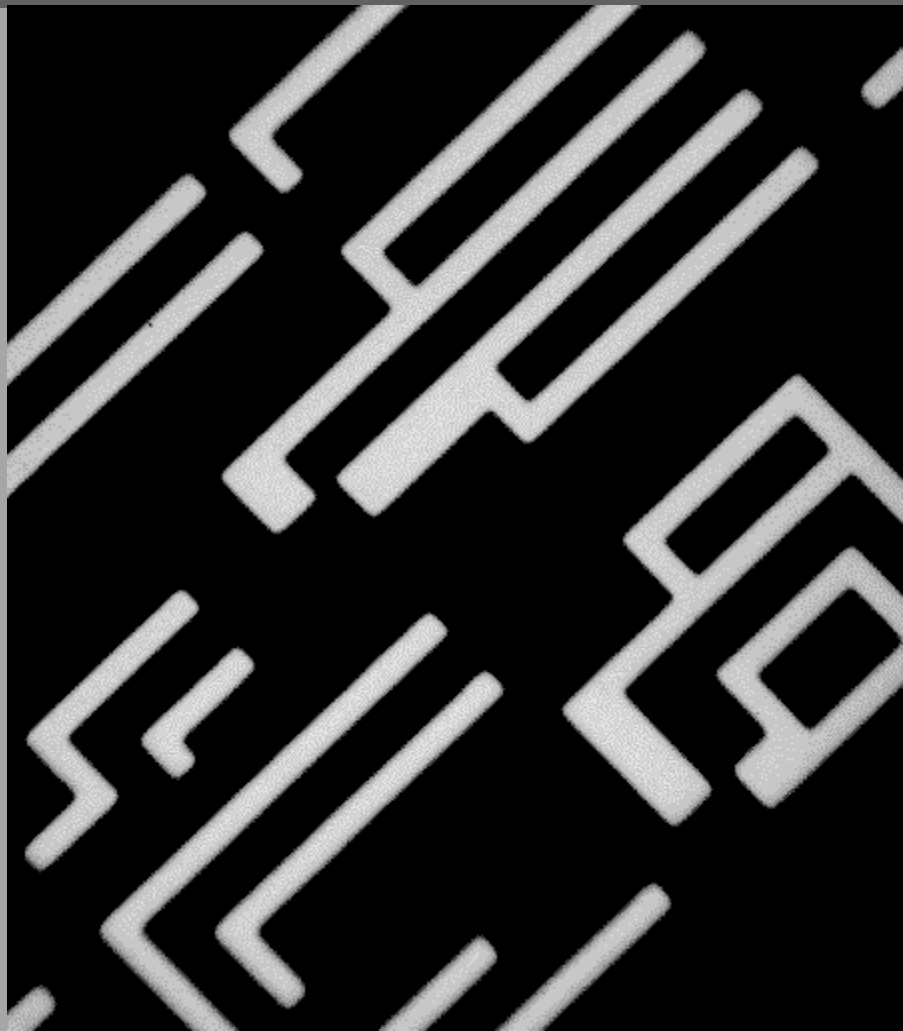
- Emulation of imaging in EUV scanner
- Emulation of anamorphic imaging
- Fully programmable illuminator
- Diffraction-limited zoneplate lenses



Summary

Camera upgrade

- Fast autofocus
- Continuous-focus stack
- Source optimization



Thanks to
our users.

Thanks to
INTEL for funding
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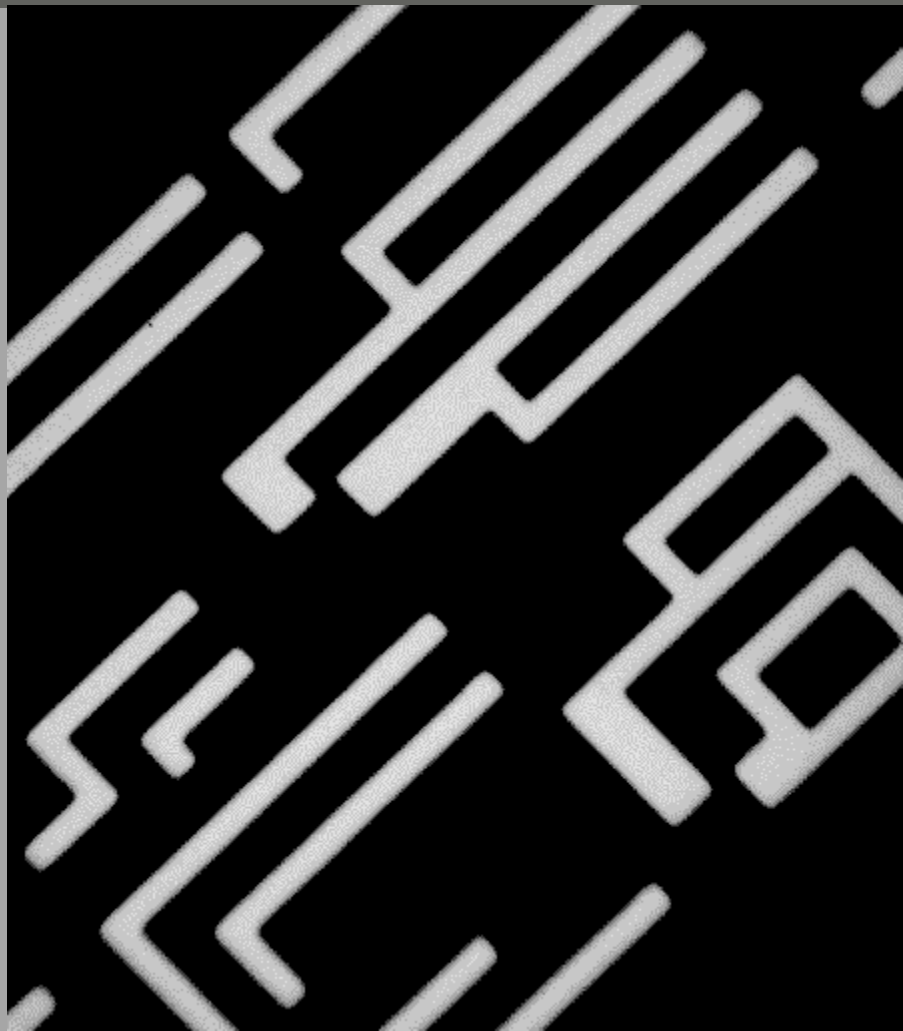

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