Coherence reduction in accelerator-based lithography systems

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EUV-FEL Workshop
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Agenda

- Intro to spatial coherence
- Coherence and imaging
- Coherence reduction methods
- Coherence reduction in high-speed applications

Acknowledgements

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CXRO
THE CENTER FOR X-RAY OPTICS

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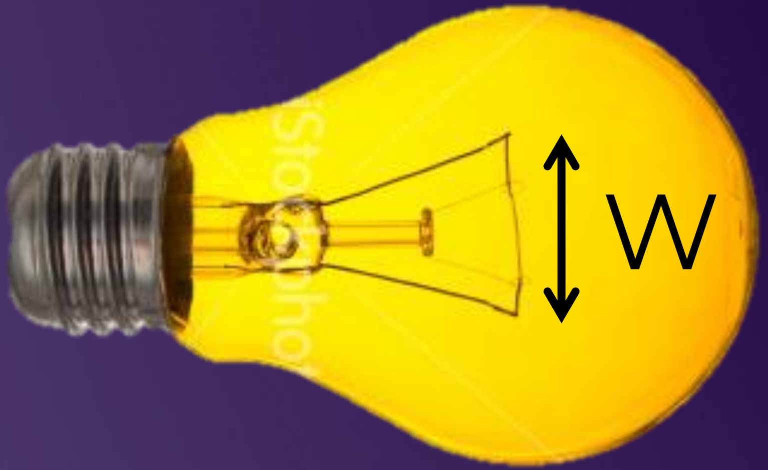

Coherence $\propto 1/W$

W = source size

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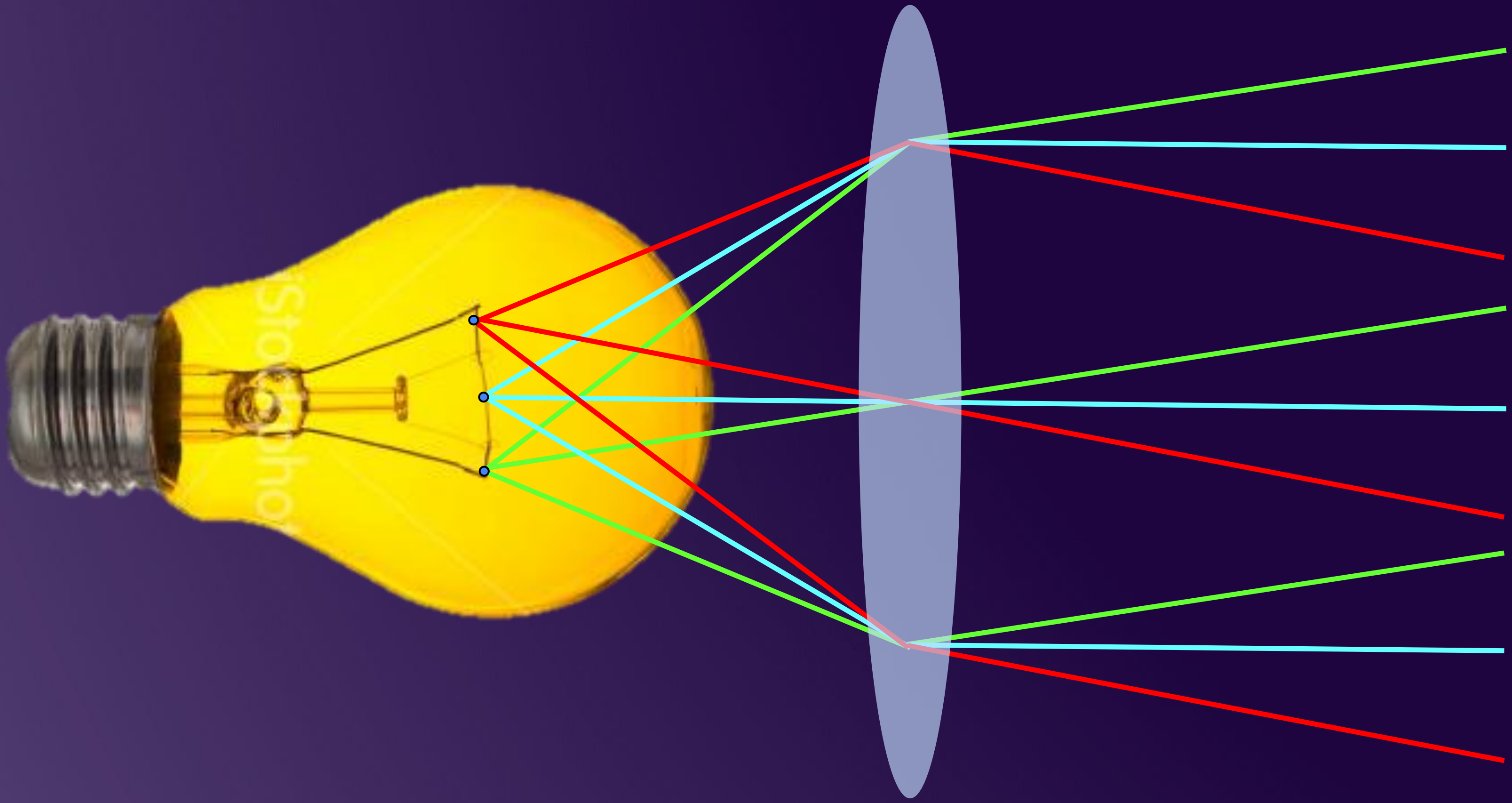

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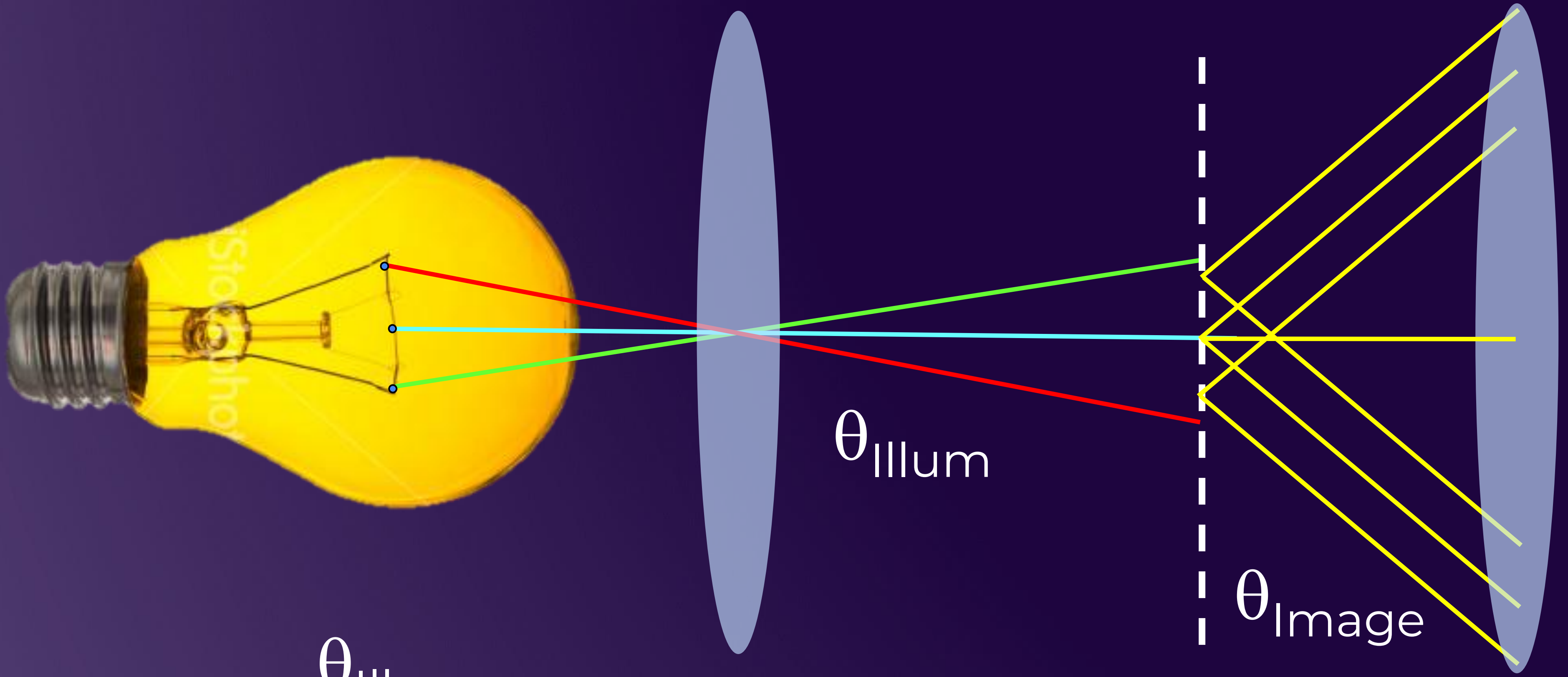

$$\sigma = \frac{\theta_{Illum}}{\theta_{Image}}$$

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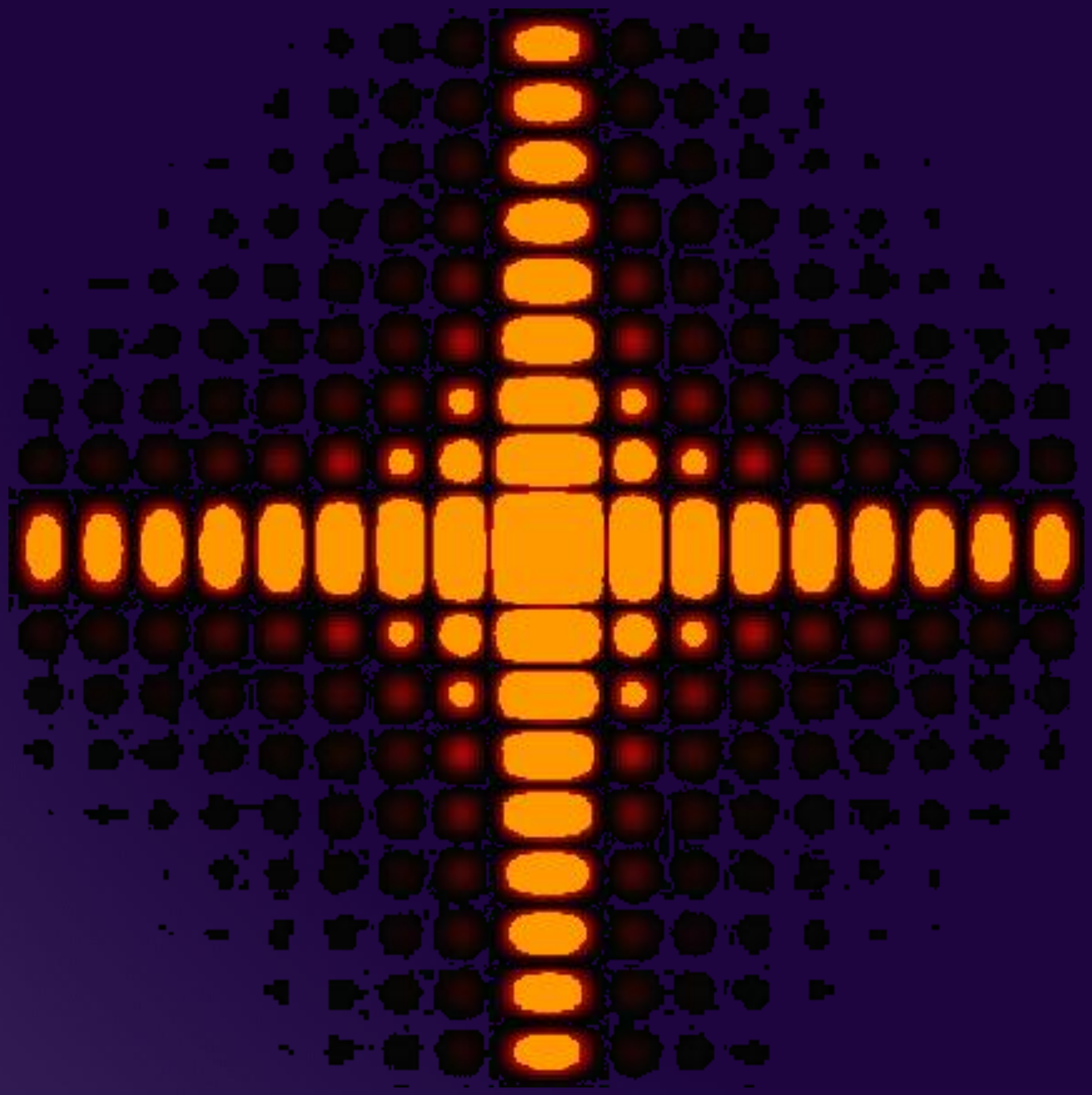
Effect of Coherence on Imaging



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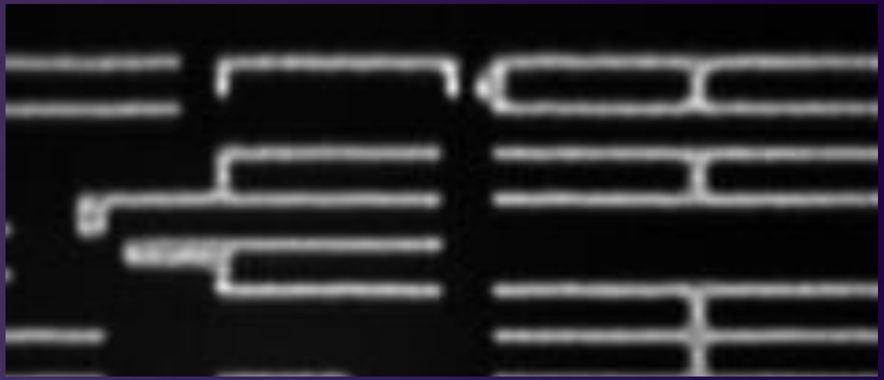
Defocus

Full coherence



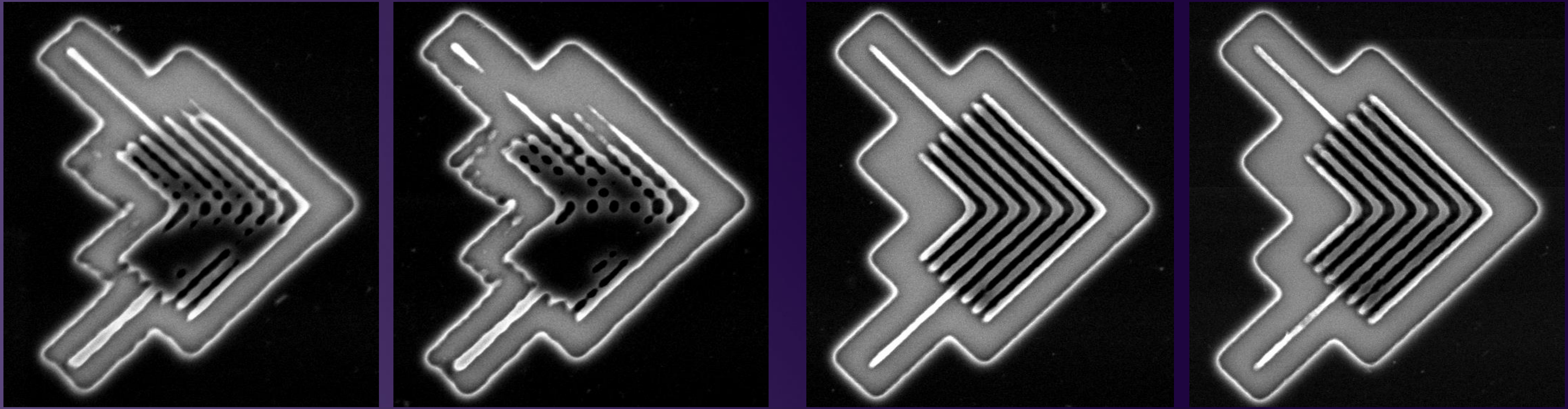
Partial coherence

Imaging from Berkeley EUV microscope

Full coherence

Partial coherence

Defocus 0 | Defocus $0.37\lambda/NA^2$ | Defocus 0 | Defocus $0.37\lambda/NA^2$



Feature half pitch = $0.52\lambda/NA$

Printing on Berkeley MET

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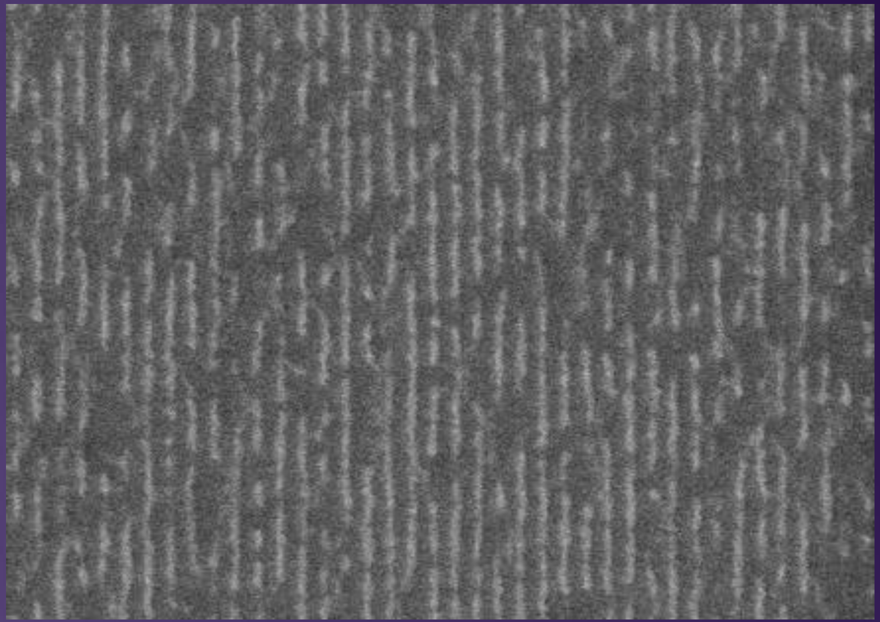
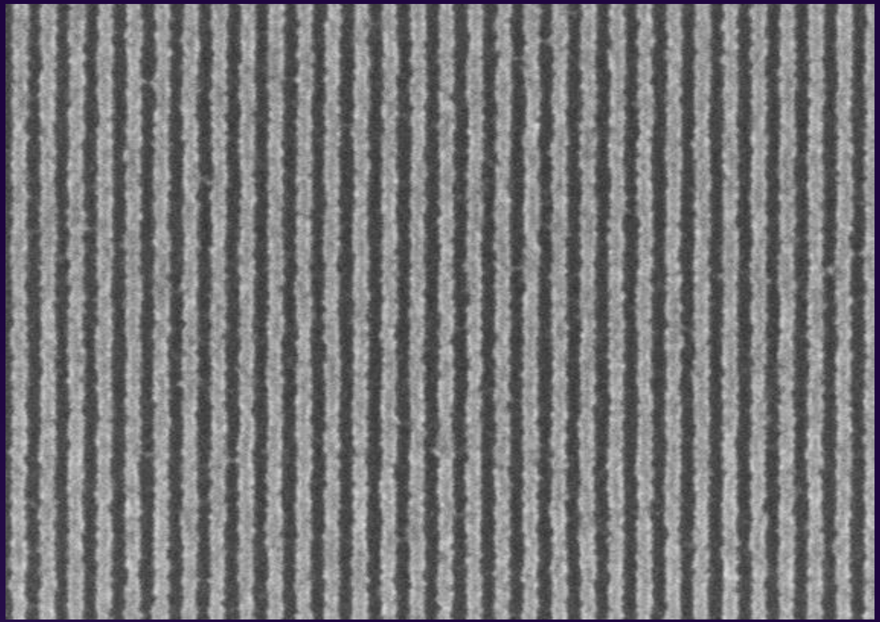
General incoherence (annular)



12-nm lines

Optimized incoherence (monopole)



9-nm lines

Printing on Berkeley MET5

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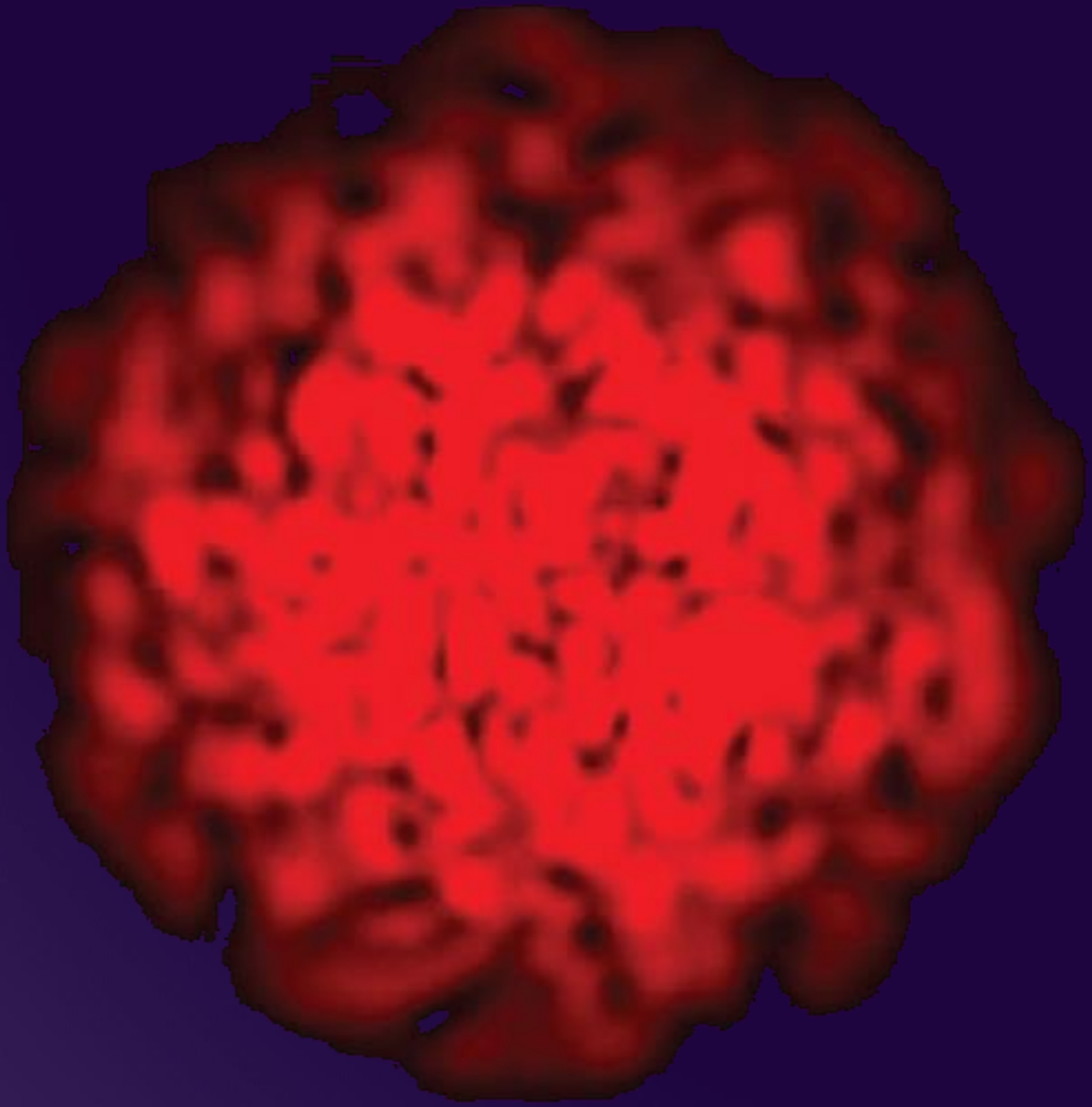
Manipulating coherence



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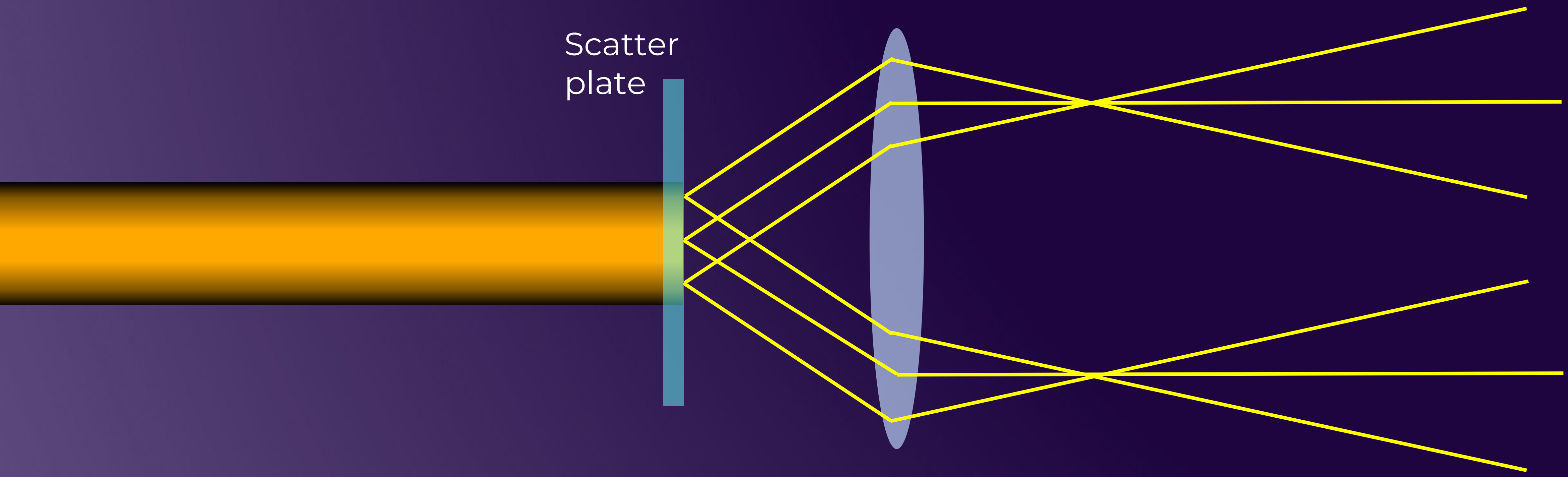
Controlling coherence (fixed scatter plate)



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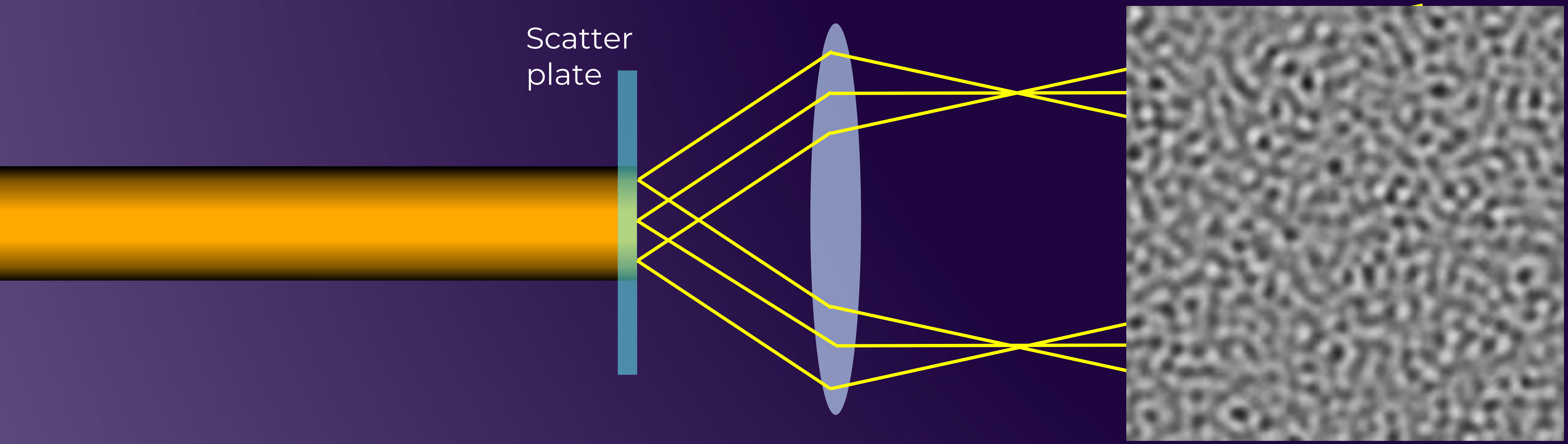
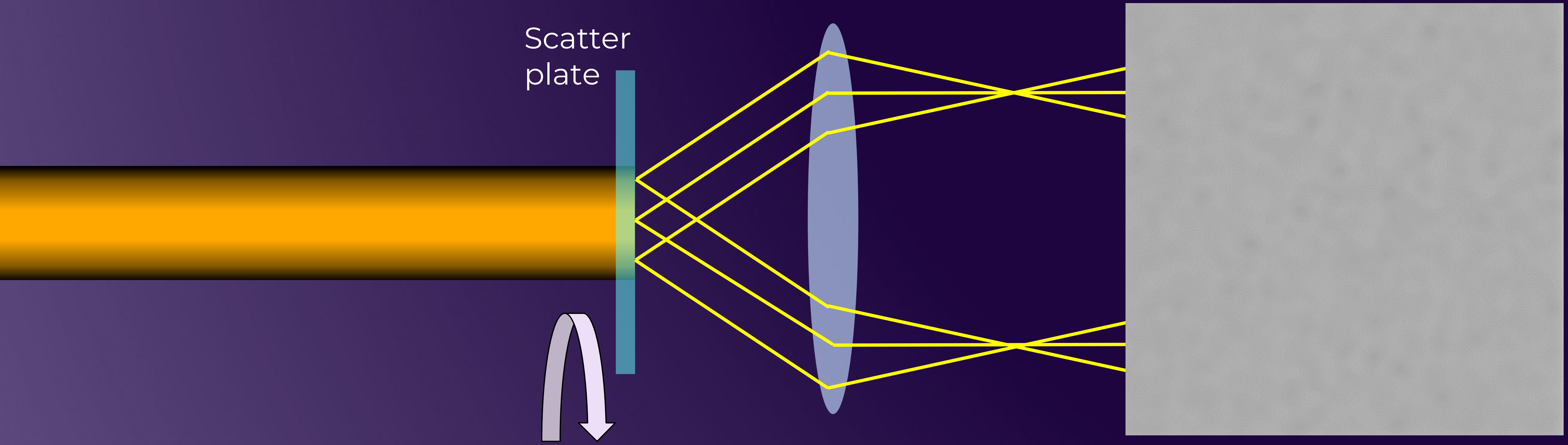
Controlling coherence (fixed scatter plate)



Controlling coherence (moving scatter plate)



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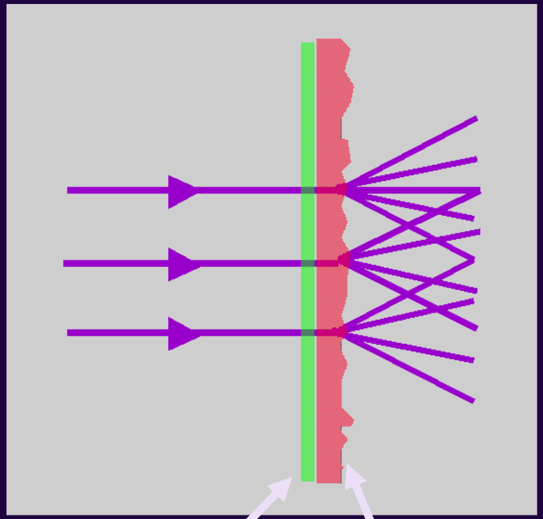
EUV transmission scatter plates are possible, but challenging and low efficiency

- Molybdenum (Mo) provides nearly optimal tradeoff between phase shift and absorption
- Si could serve as efficient membrane and cap



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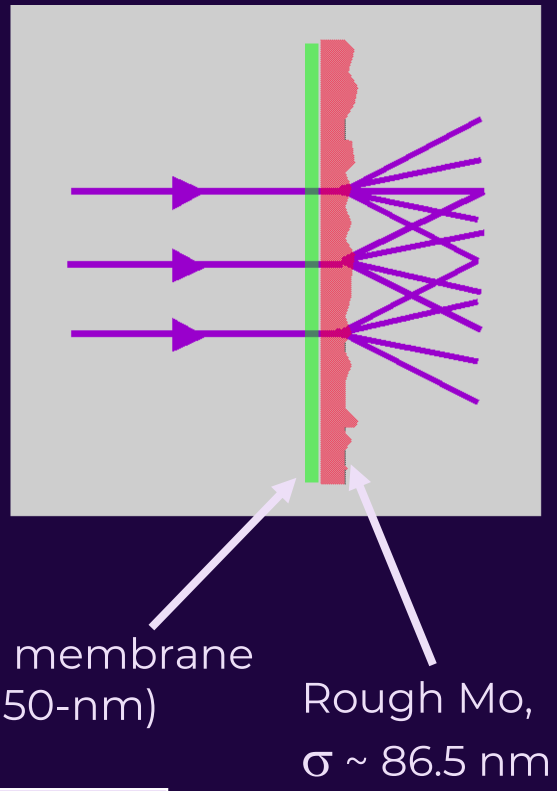
EUV transmission scatter plates are possible, but challenging and low efficiency

- Molybdenum (Mo) provides nearly optimal tradeoff between phase shift and absorption
- Si could serve as efficient membrane and cap
- EUV scatter plate case study:
  - 0.1375-NA half-max diffuser (100-nm period structure)
  - 0.1375-NA collection angle
  - <1% specular light
  - 55-nm Si membrane + cap
  - 50-nm bulk Mo (~10% of modulated Mo thickness)

0.91	Si throughput
0.75	bulk Mo throughput
0.12	modulated Mo throughput
0.45	collected fraction
3.7%	total efficiency



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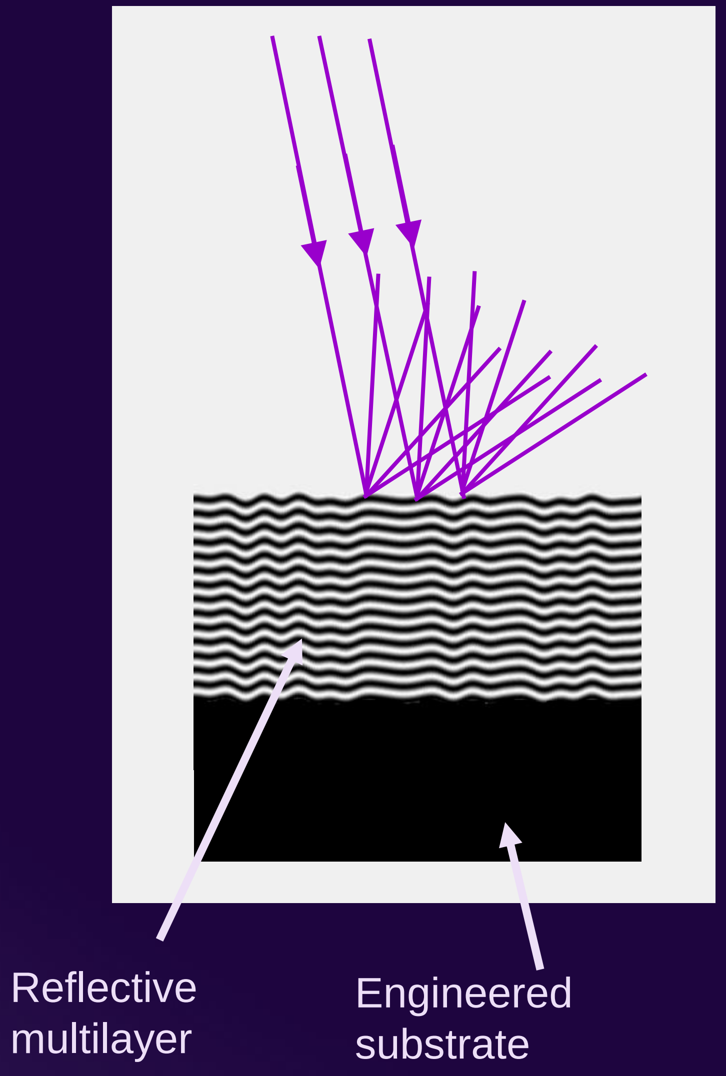
Reflection scatter plate can be more efficient

- Most efficient solution is overcoated engineered roughness substrate
- Zero effective absorption loss possible if scatter plate can be integrated on otherwise needed mirror
- Challenges:
  - Hard to achieve 100-nm period structure due to multilayer smoothing
  - Hard to achieve well-controlled scatter angle profile



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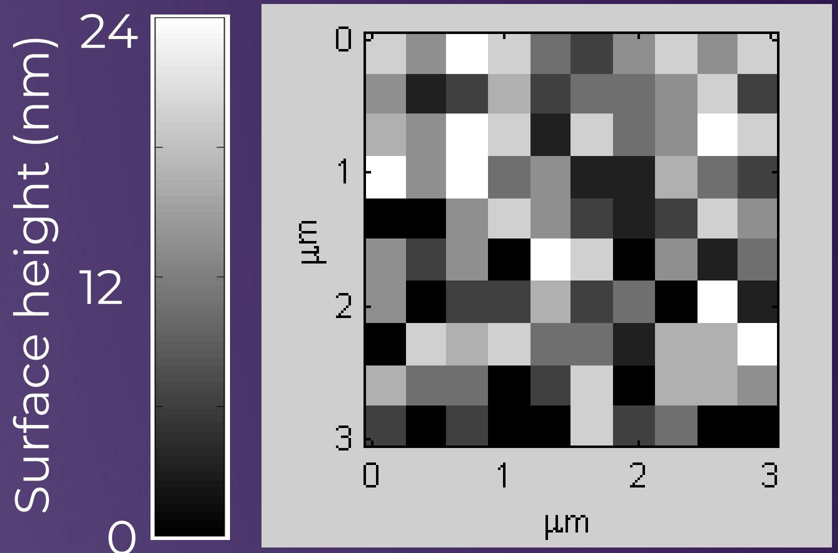
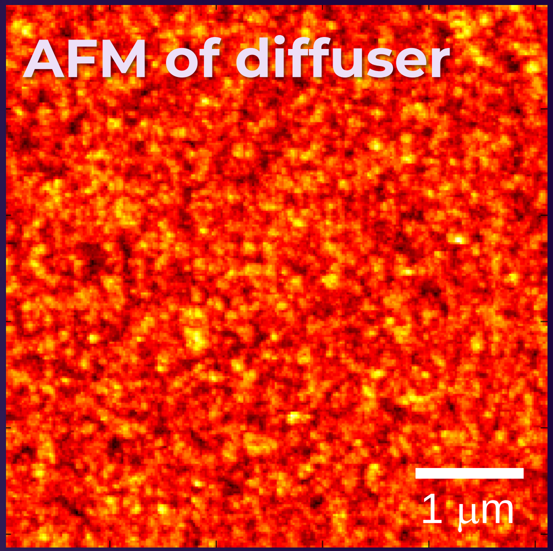
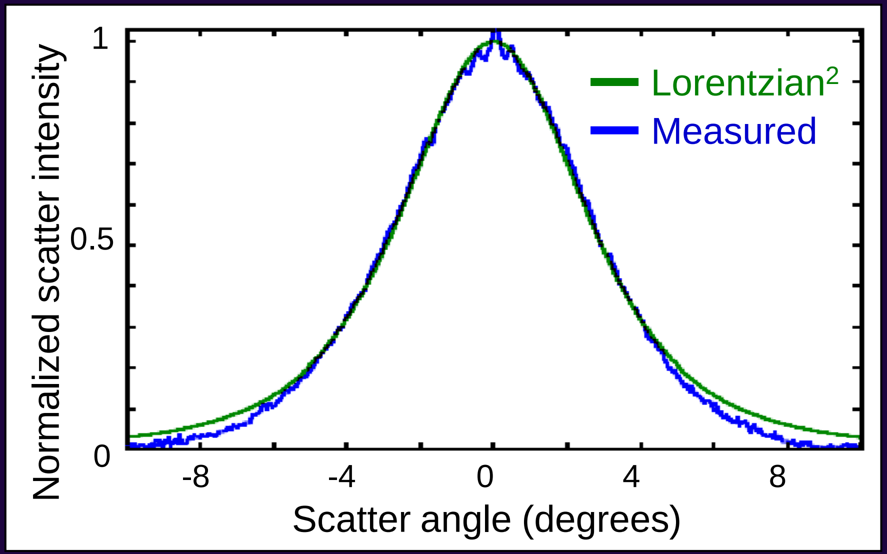
Demonstration of engineered roughness diffuser







- Pseudo-random surface design
- Cell size = 100 nm for 0.06 scatter NA

- Use grayscale lithography to produce substrate
- Apply ML coating

- EUV measured scatter profile
- 11% efficiency within 0.06 NA
- 17% effective efficiency if integrated into existing mirror
- Intensity ~40% at 0.06 NA

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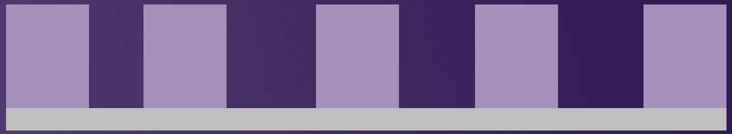
Scatter angle control with high efficiency possible with holographic optical element

Mo on Si Membrane

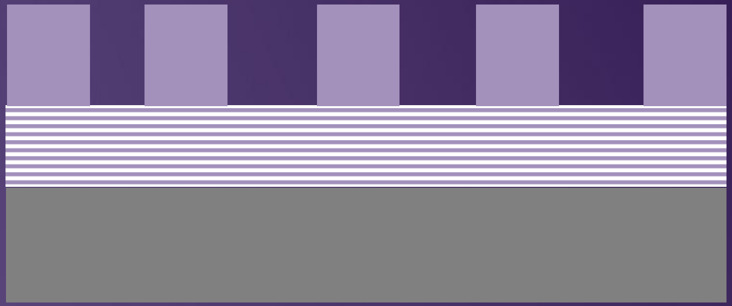


1st Order
29%

Etched Mo/Si multilayer

1st Order
27%

Mo on Mo/Si Multilayer

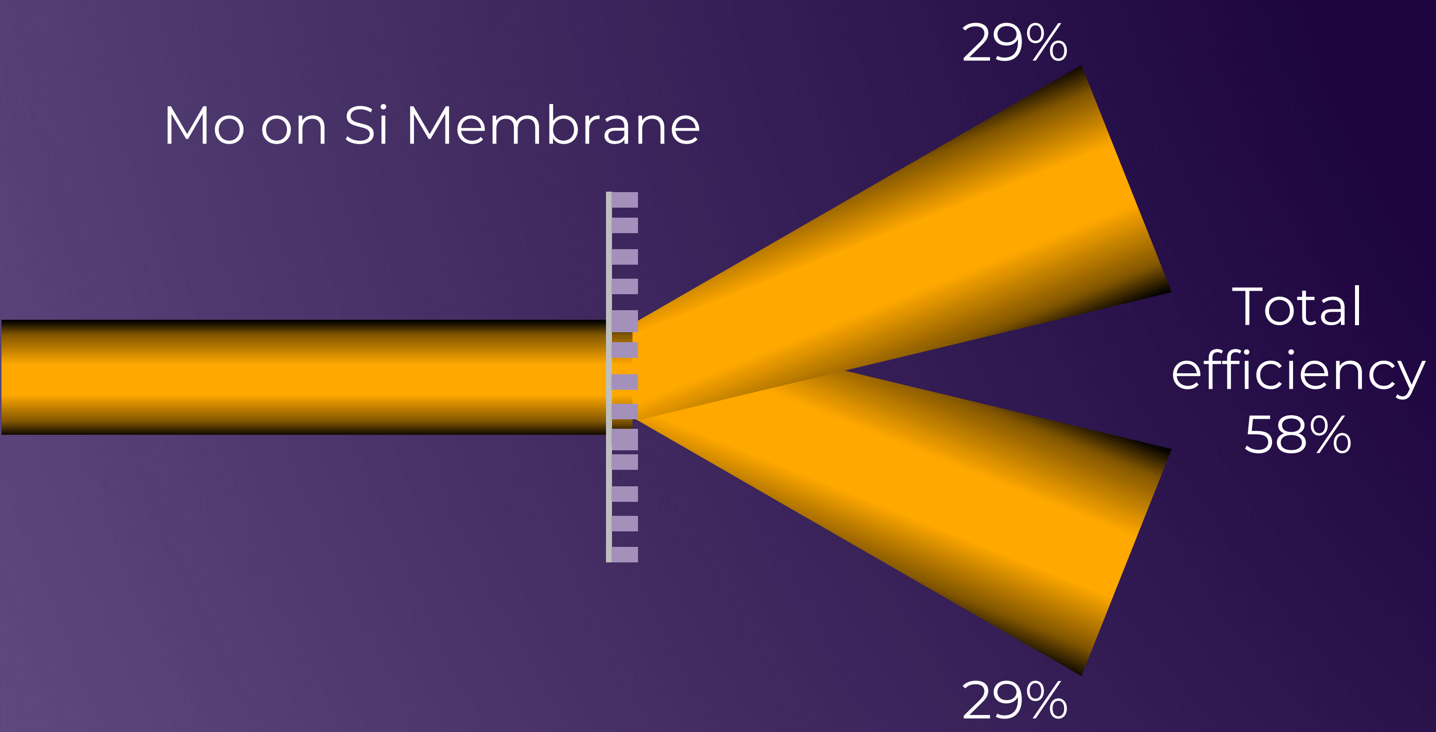


1st Order
22%

Mo/Si multilayer on relief substrate

1st Order
27%

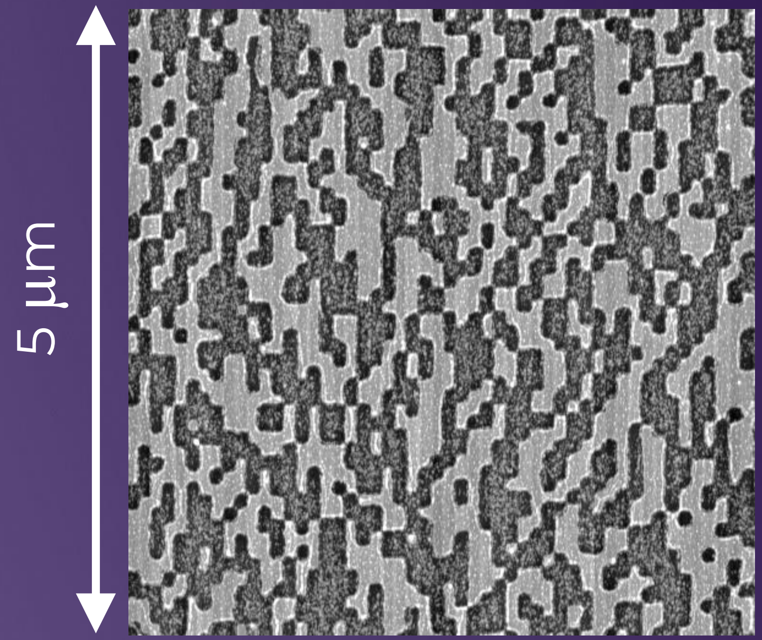
Even higher efficiency possible with symmetric pupil fills

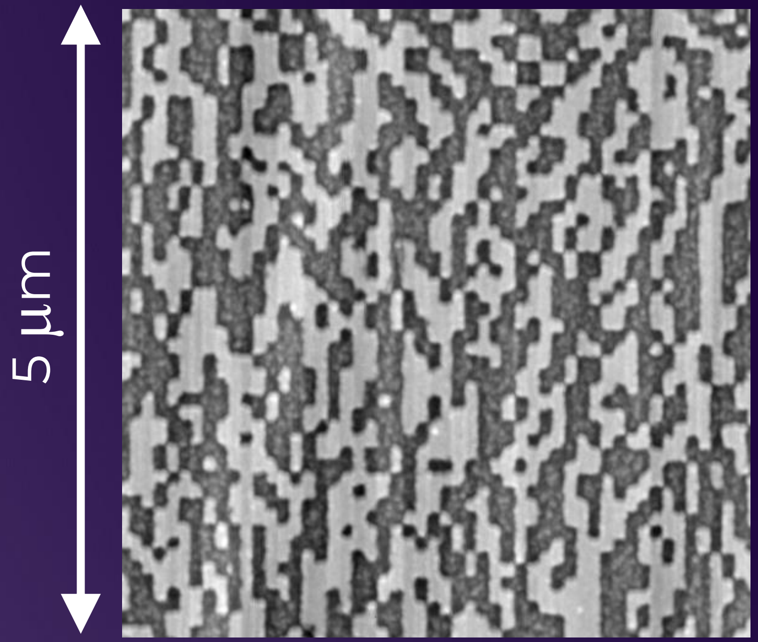


- Binary carrier holographic devices will produce symmetric diffraction orders
- When axially symmetric illumination patterns are desired, the total efficiency of the device can be double

Demonstration of multilayer relief structure HOE

AFM images from HOE





- HOE designed to create two poles: each pole having NA = 0.042 x 0.026
- Design pixel size = 98 nm

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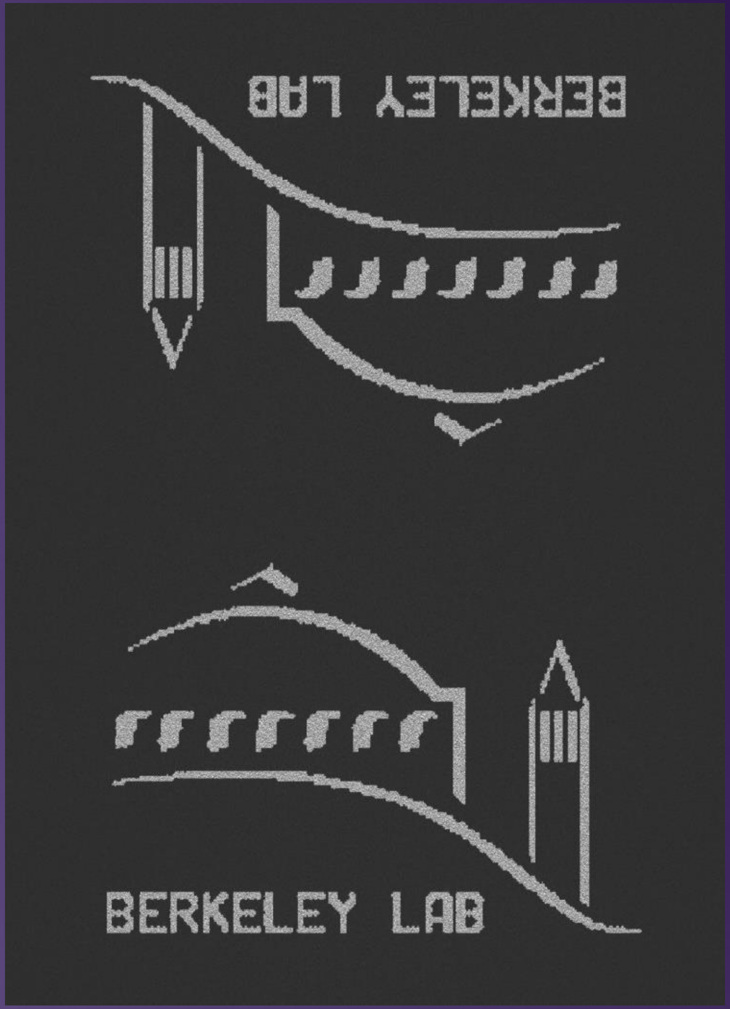
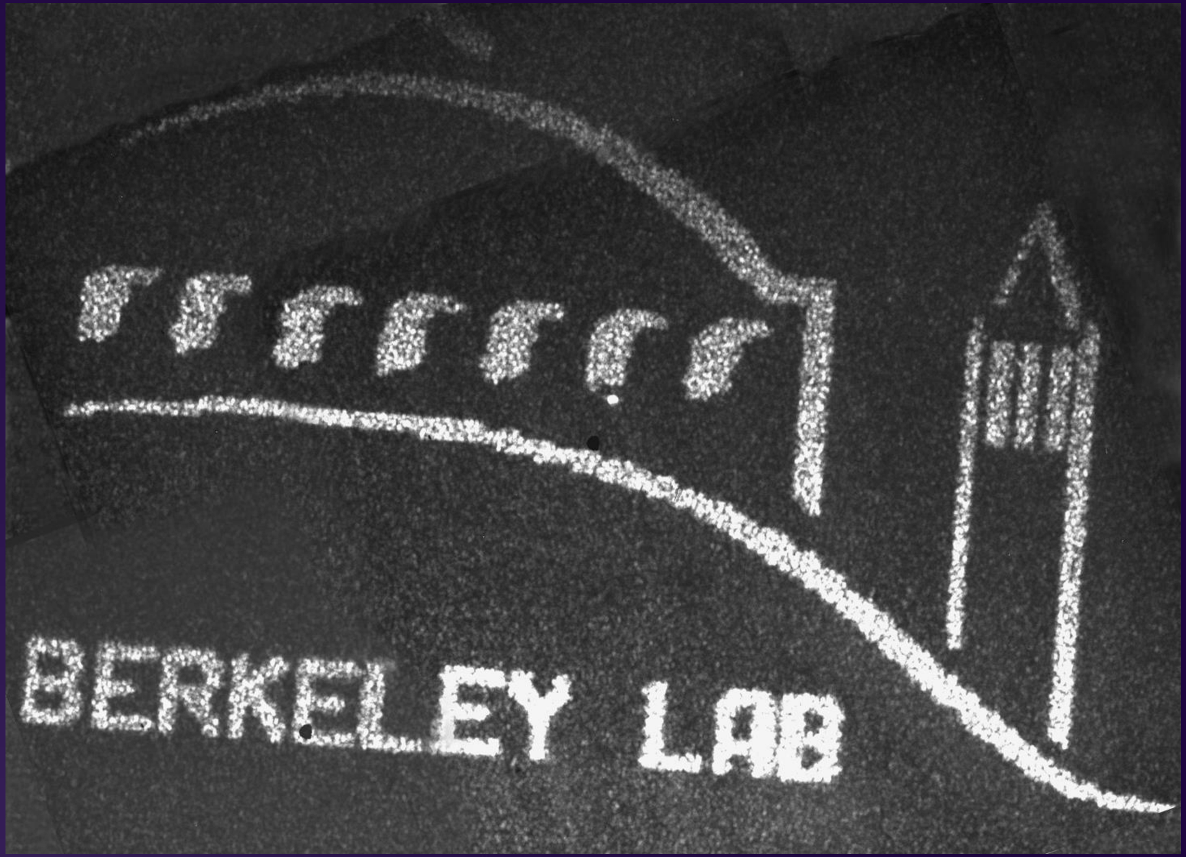
Demonstration of multilayer relief structure HOE

Predicted



Measured +1 order only



Measured at CXRO beamline 6.3.2

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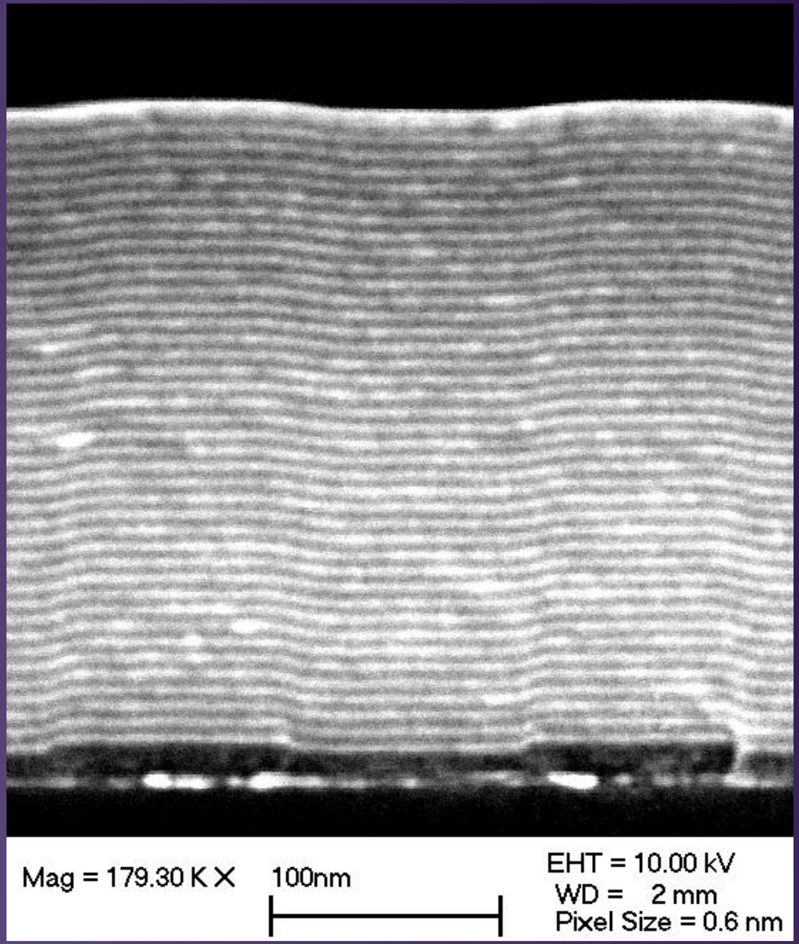
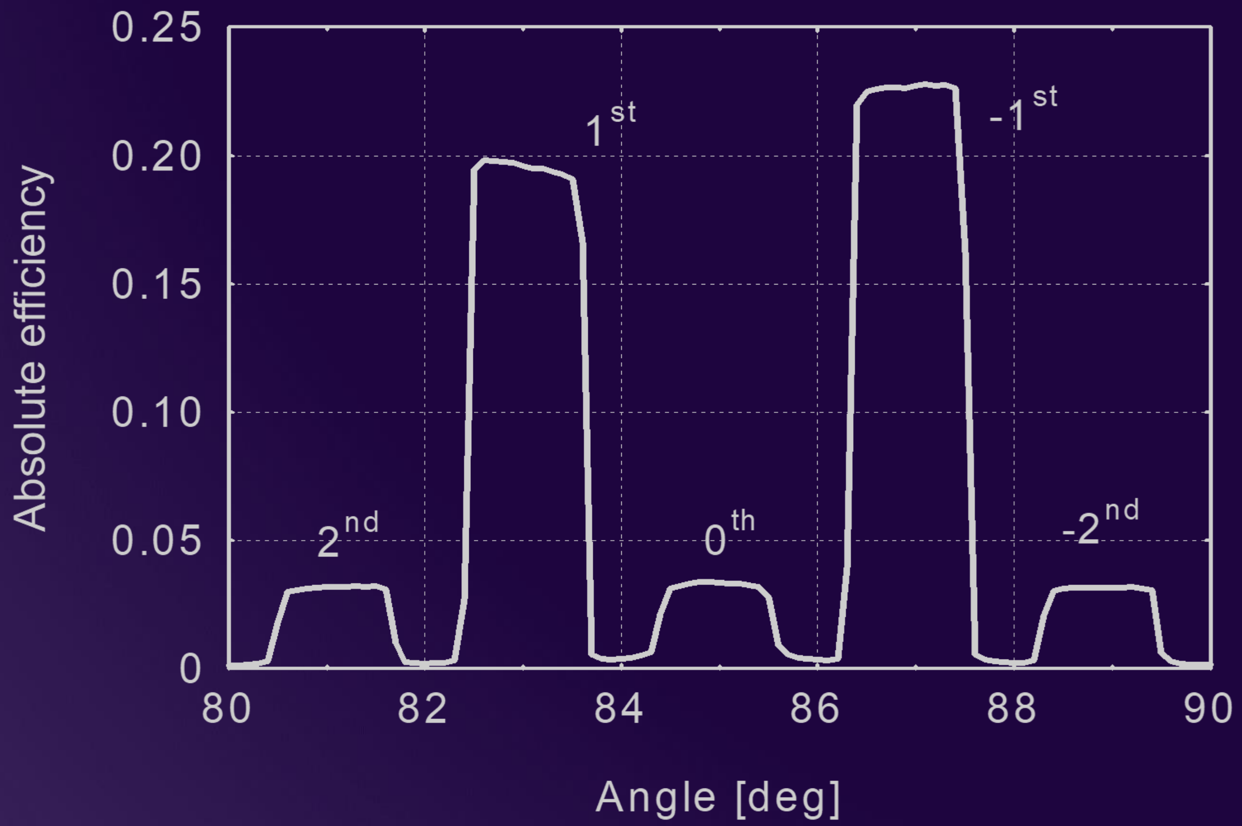
Relief HOE efficiency



Effective first order efficiency of 43% achieved



Measured at CXRO beamline 6.3.2

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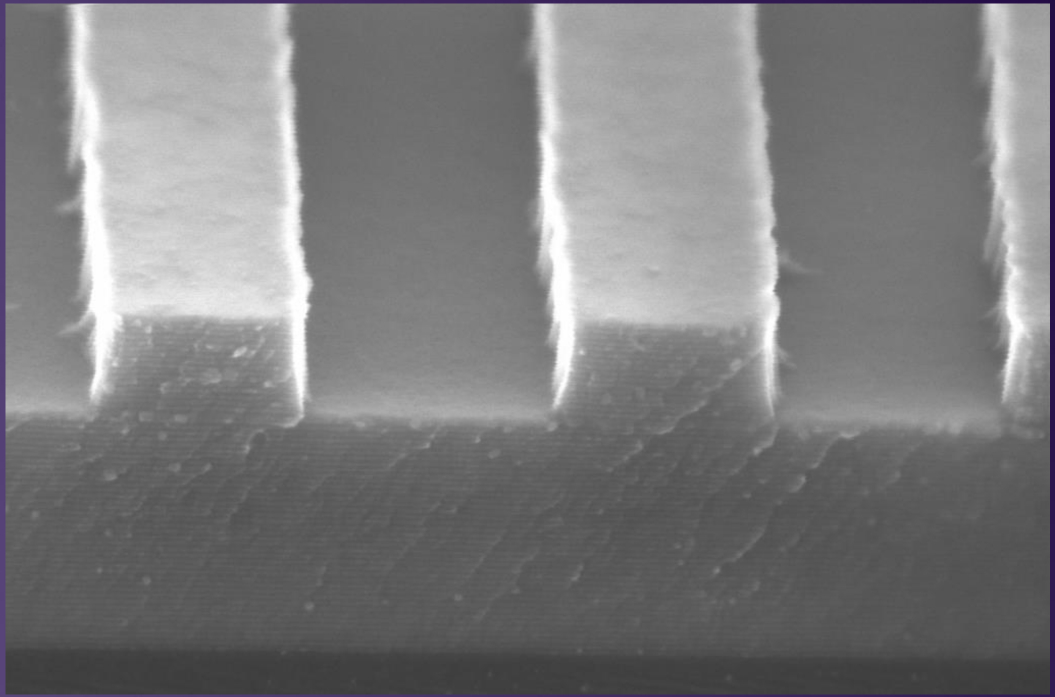
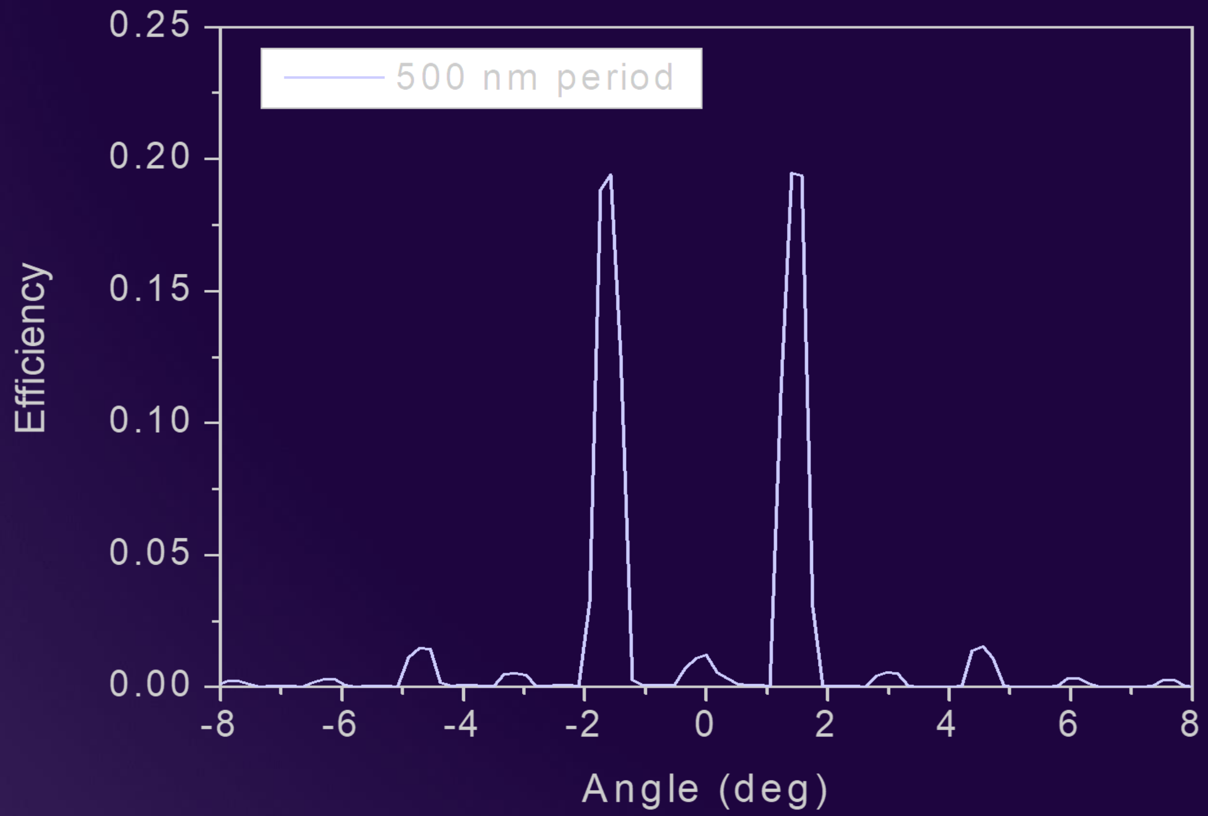
Etched multilayer HOE efficiency



Effective first order efficiency of 38% achieved



Measured at CXRO beamline 6.3.2

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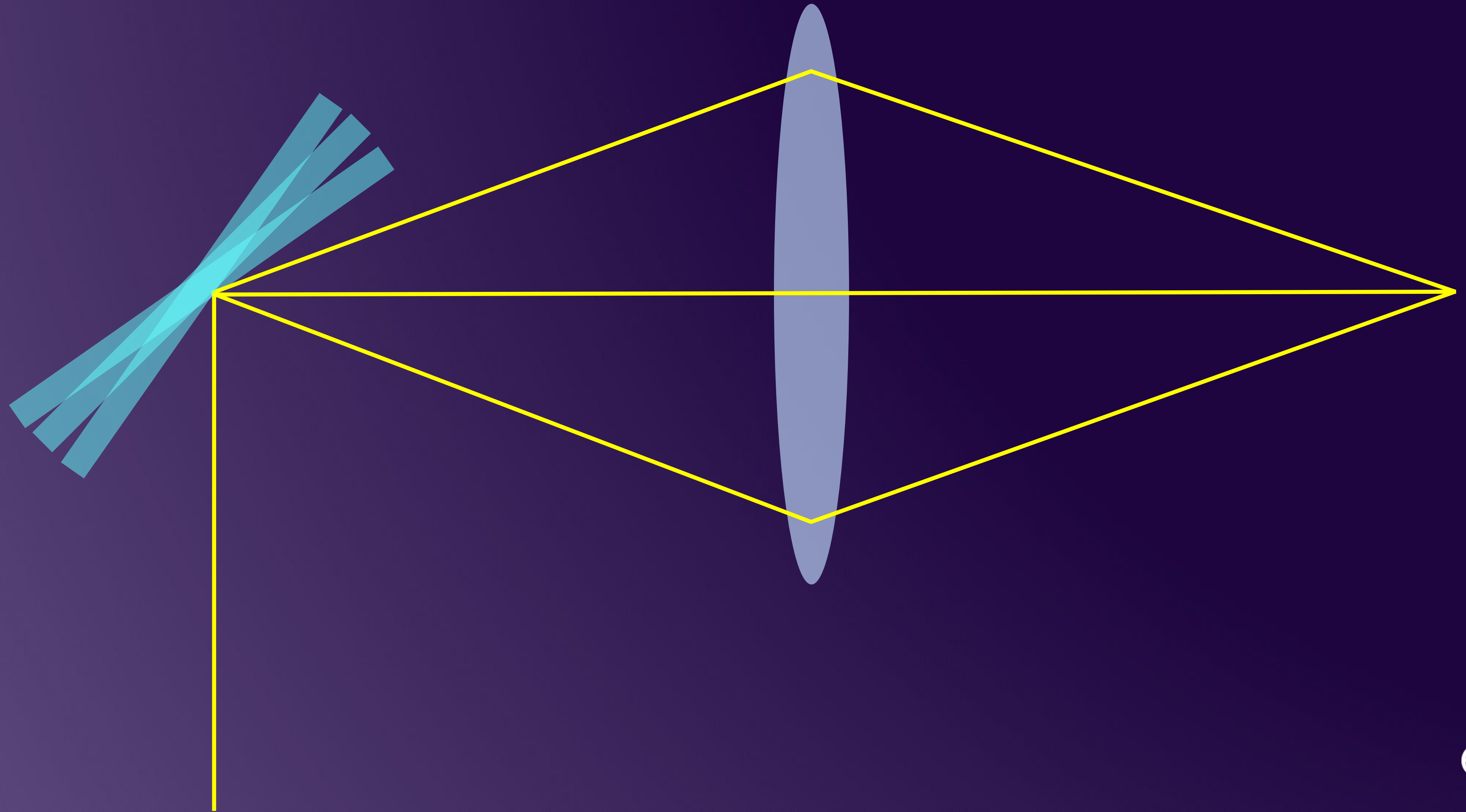
Controlling coherence (angle scanner)



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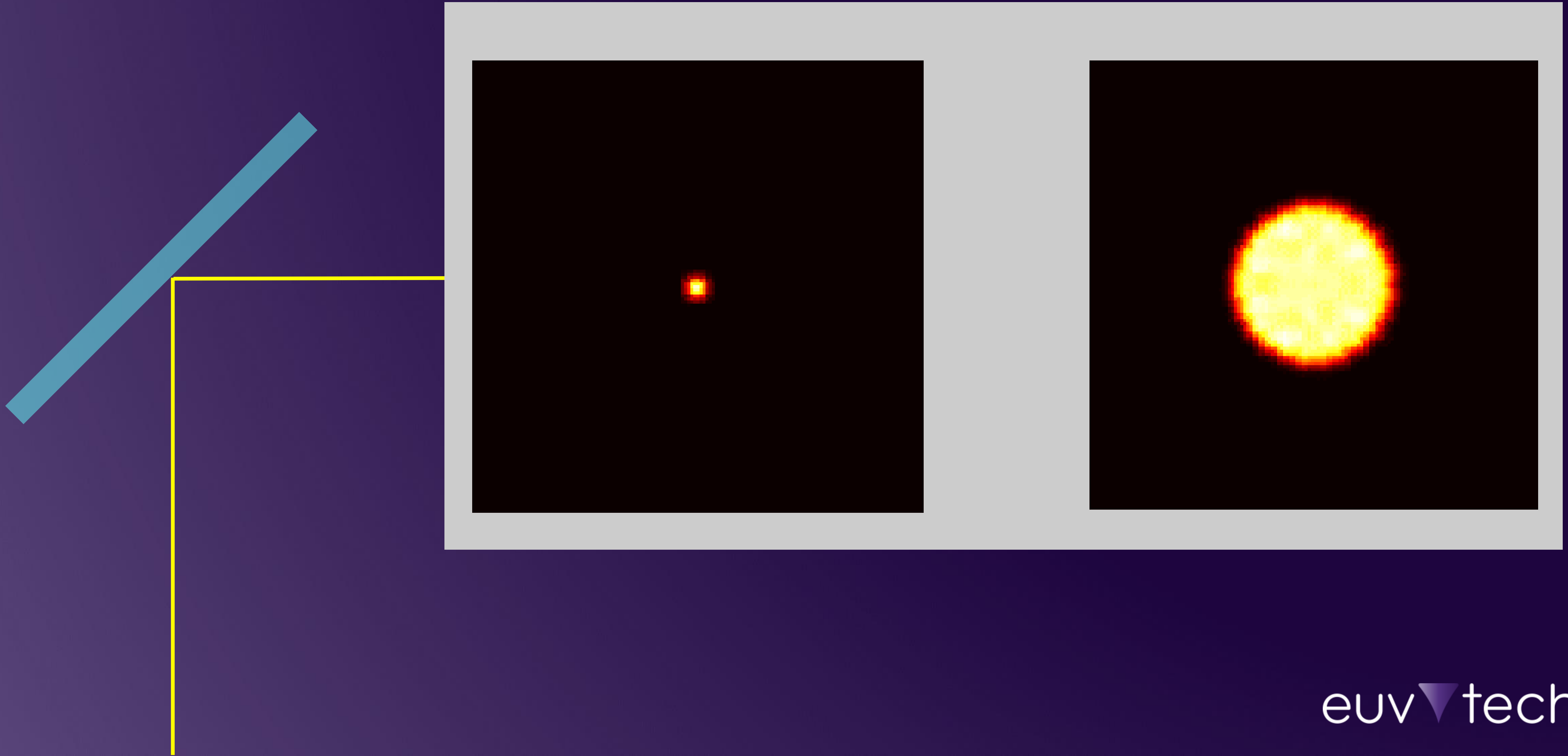
Controlling coherence (angle scanner)



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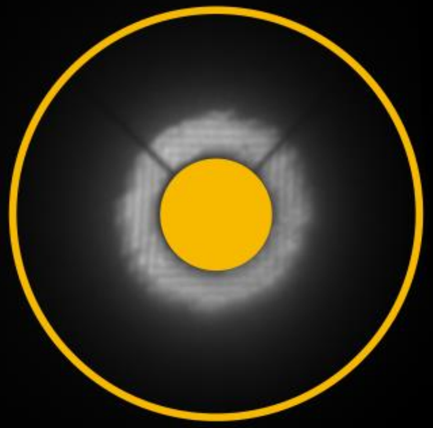
Scanner generated illuminations on Berkeley MET5

"LEAF" QUAD

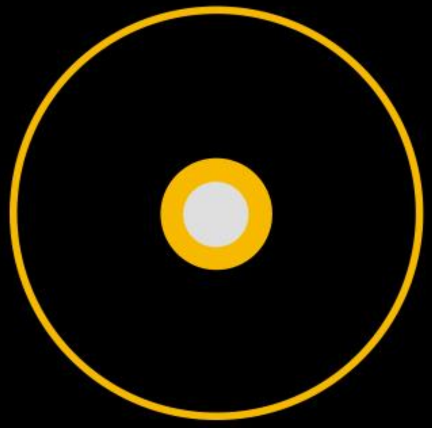
QUASAR



GRIDDED ANNULAR

GRIDDED ANNULAR

"LEAF" DIPOLE



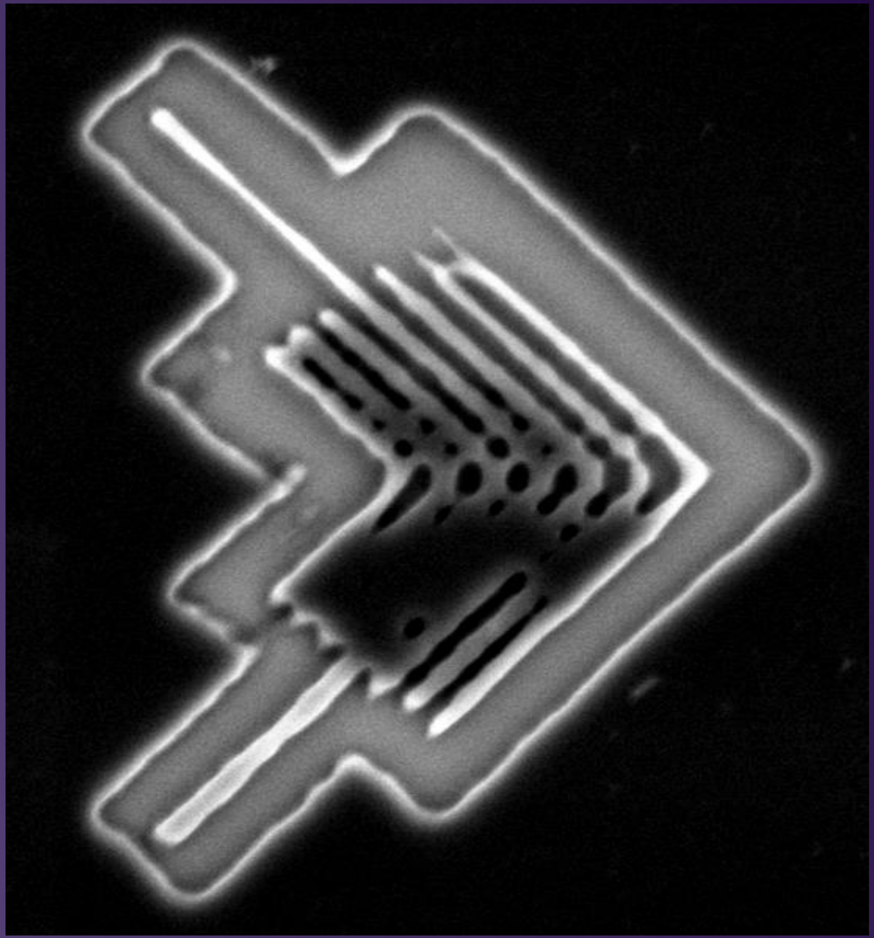
FREQUENCY DOUBLING
*NOT REAL IMAGE

HEXAPOLE

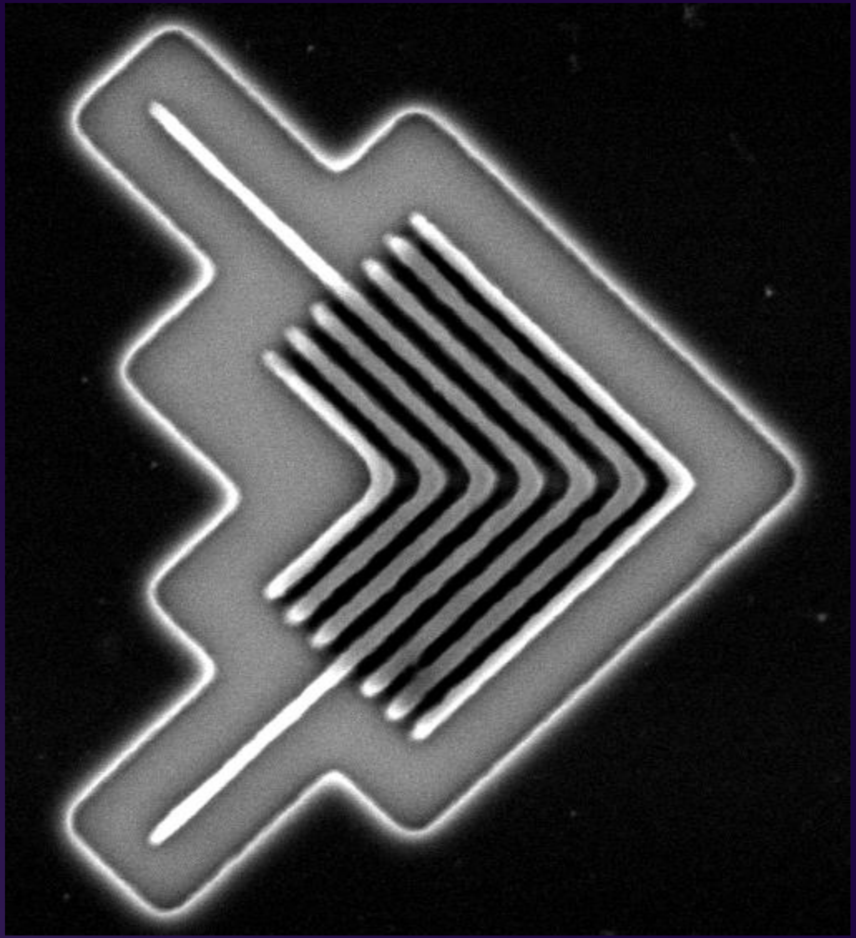
QUASAR 2

Imaging on Berkeley MET (undulator beamline)

Scanner off



Scanner on



Feature half pitch = 0.52λ/NA, from Berkeley MET

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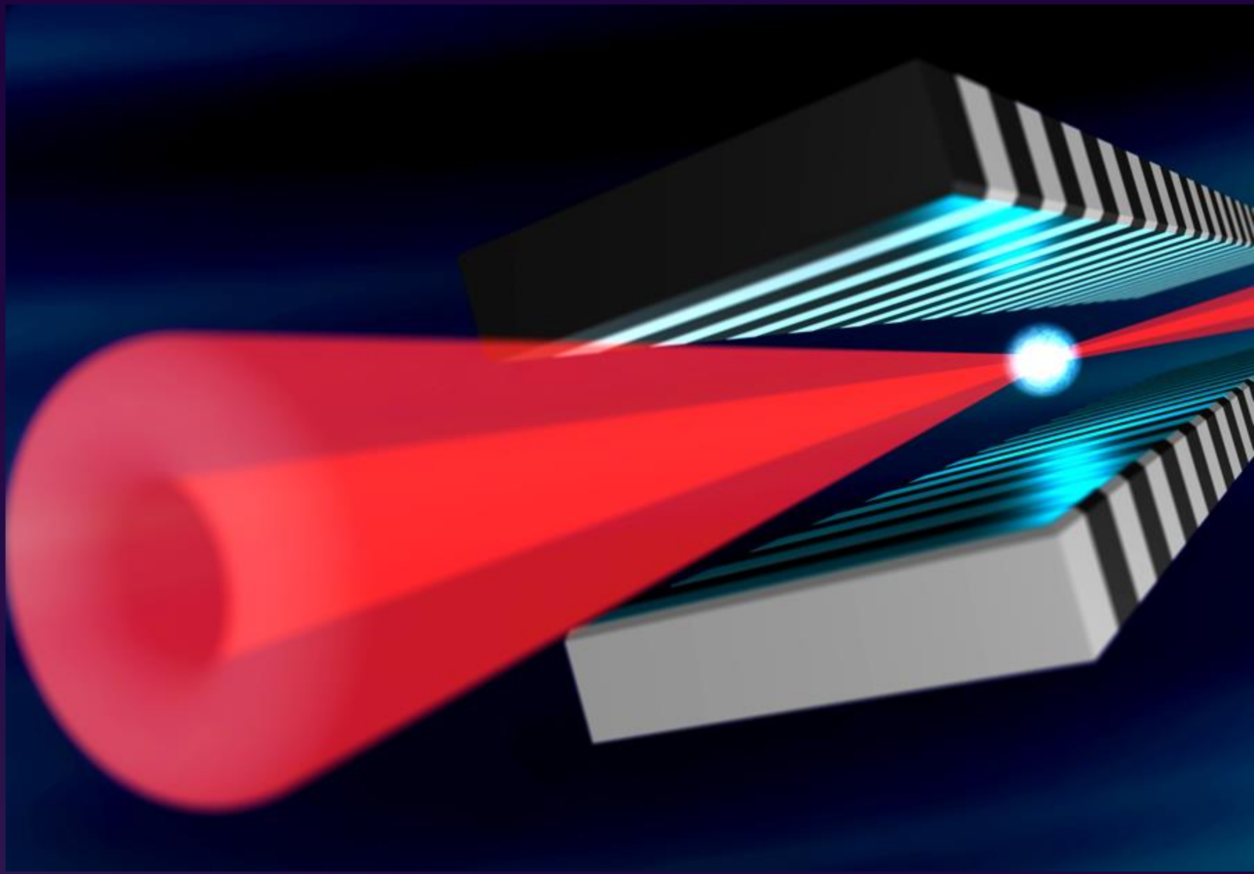
Applicability to Free Electron Lasers



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Scanner not suitable for key FEL applications

- Ultrafast single pulse imaging effectively freezes the scanner
- High speed commercial litho also a problem
  - Slit integration time = 1 ms
  - Required modes = 100
  - Required angle step rate = 100 kHz

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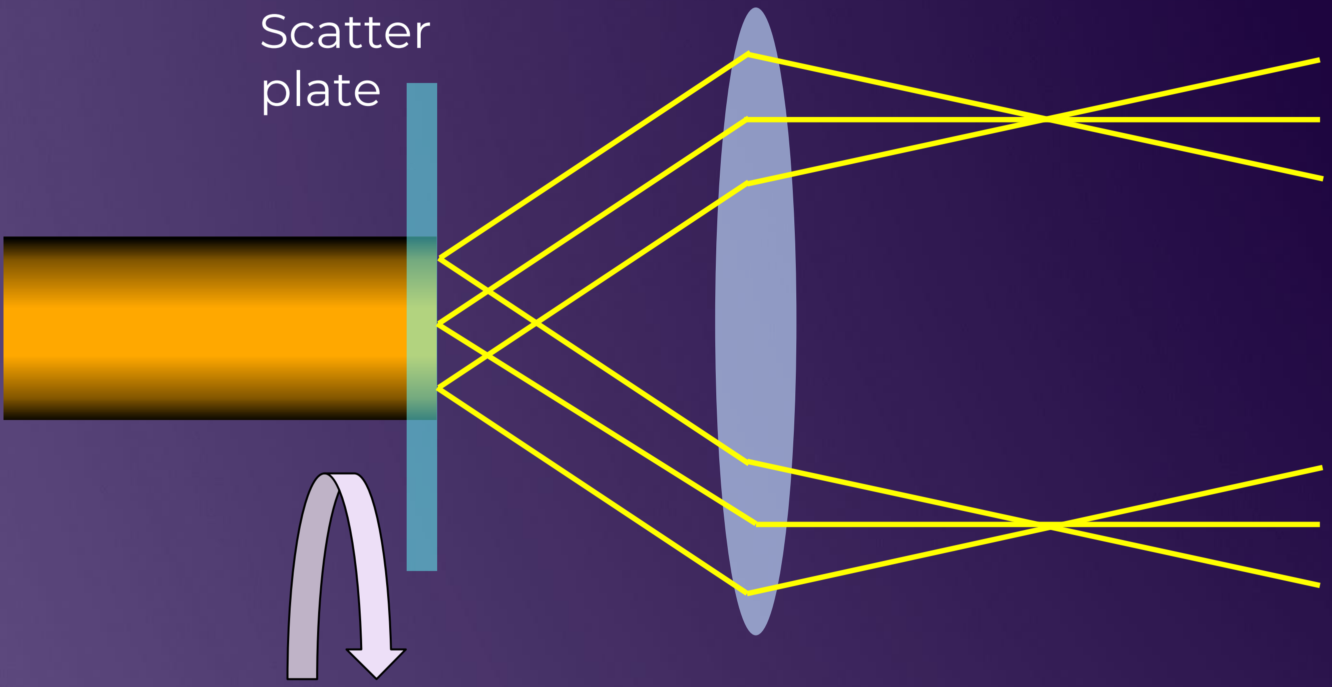
Would scatter plate work for FEL?



- Same problem with single pulse
- High speed litho requirement:
  - Slit integration time = 1 ms
  - Assume 100-mm beam size
  - Required modes = 100
  - Required scan speed = 100 km/s

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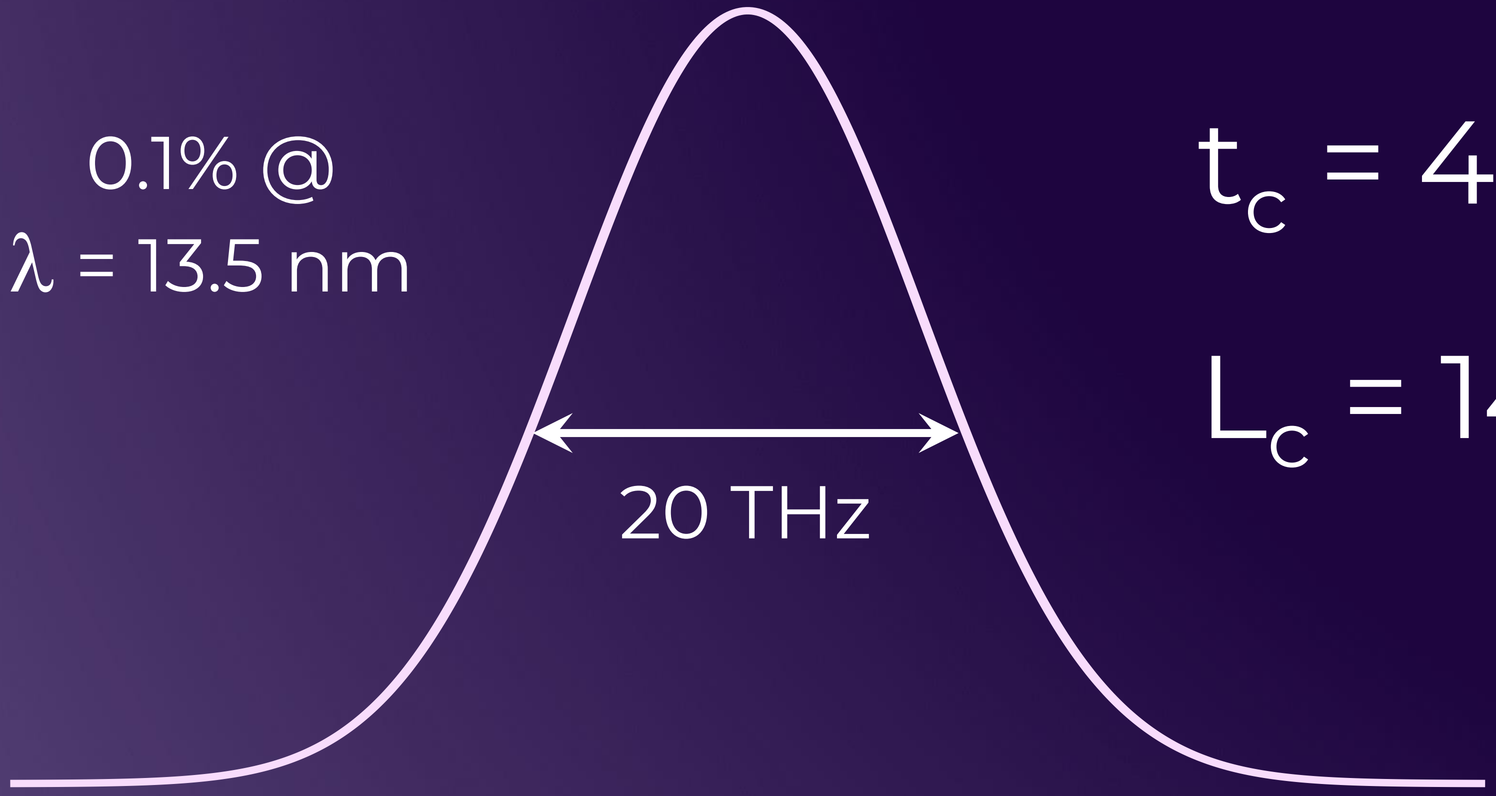
Leveraging FEL temporal properties

- Although FELs have high spatial coherence, temporal bandwidth is large on absolute scale

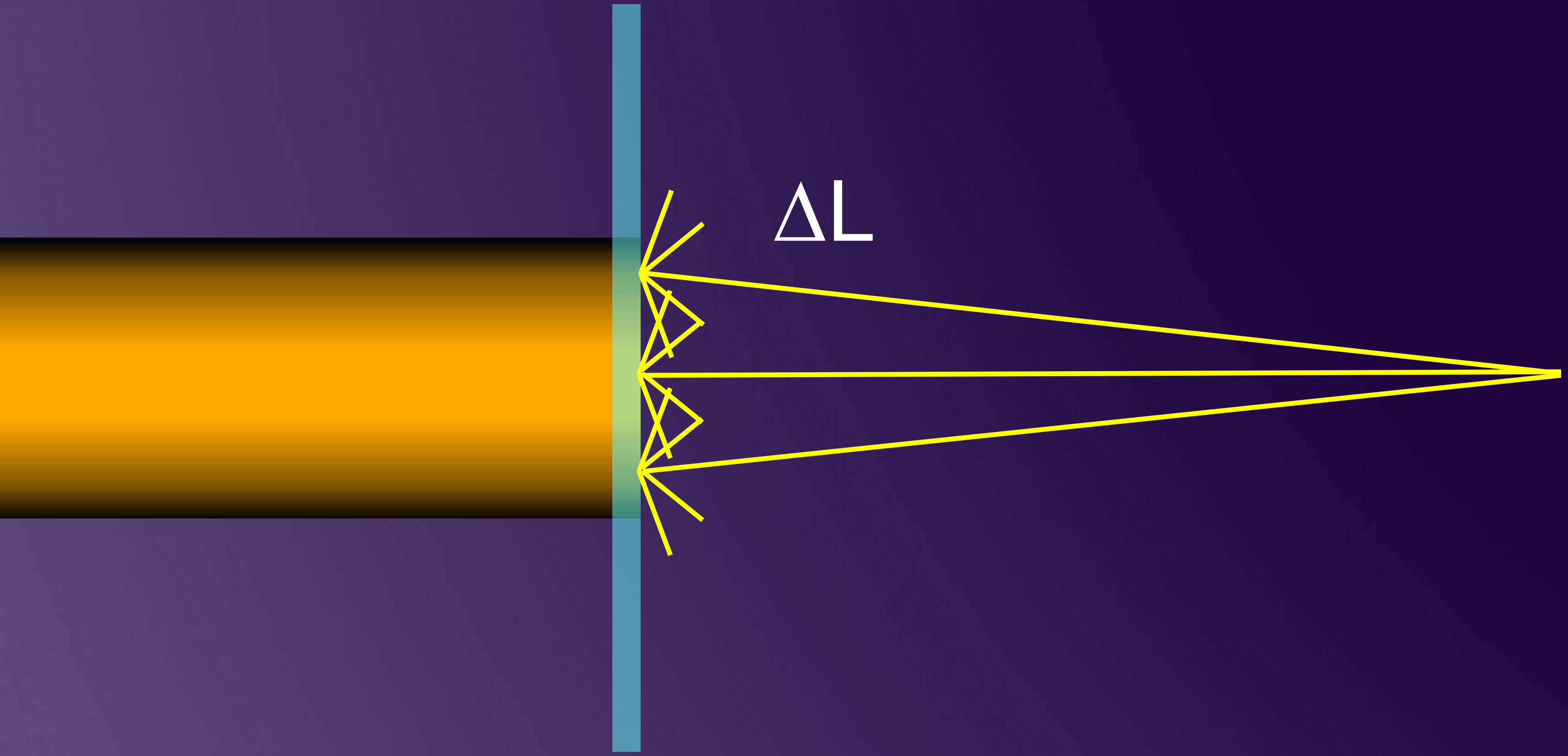
0.1% @
λ = 13.5 nm



t_c = 45 fs

L_c = 14 μm

Temporal to spatial incoherence transformation is possible



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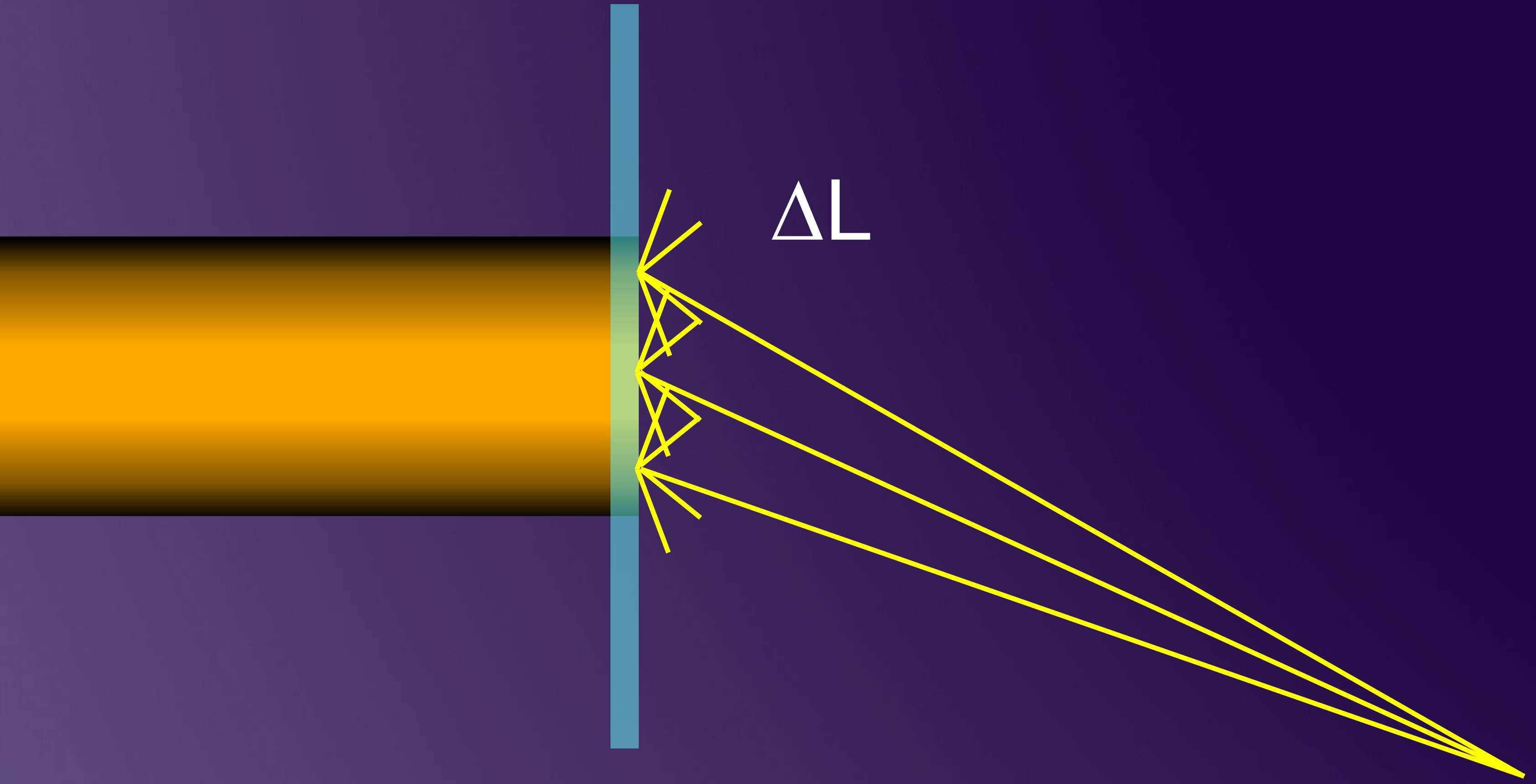

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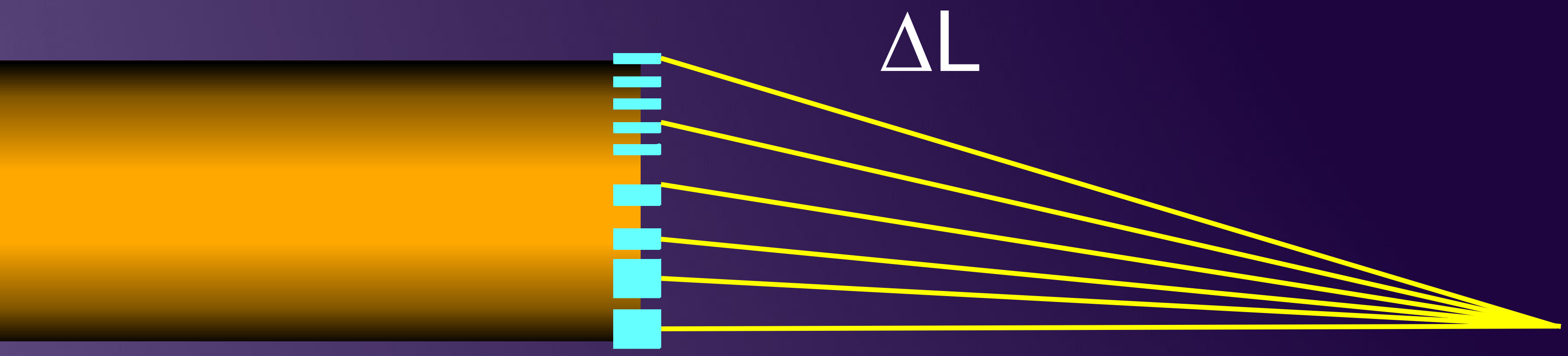
Temporal to spatial incoherence transformation is possible



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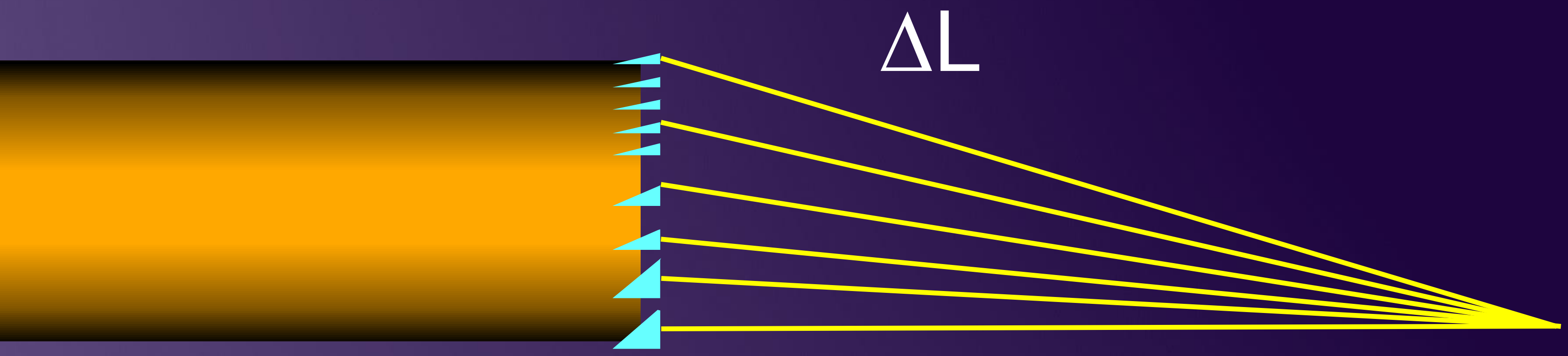
Temporal to spatial incoherence transformation is possible



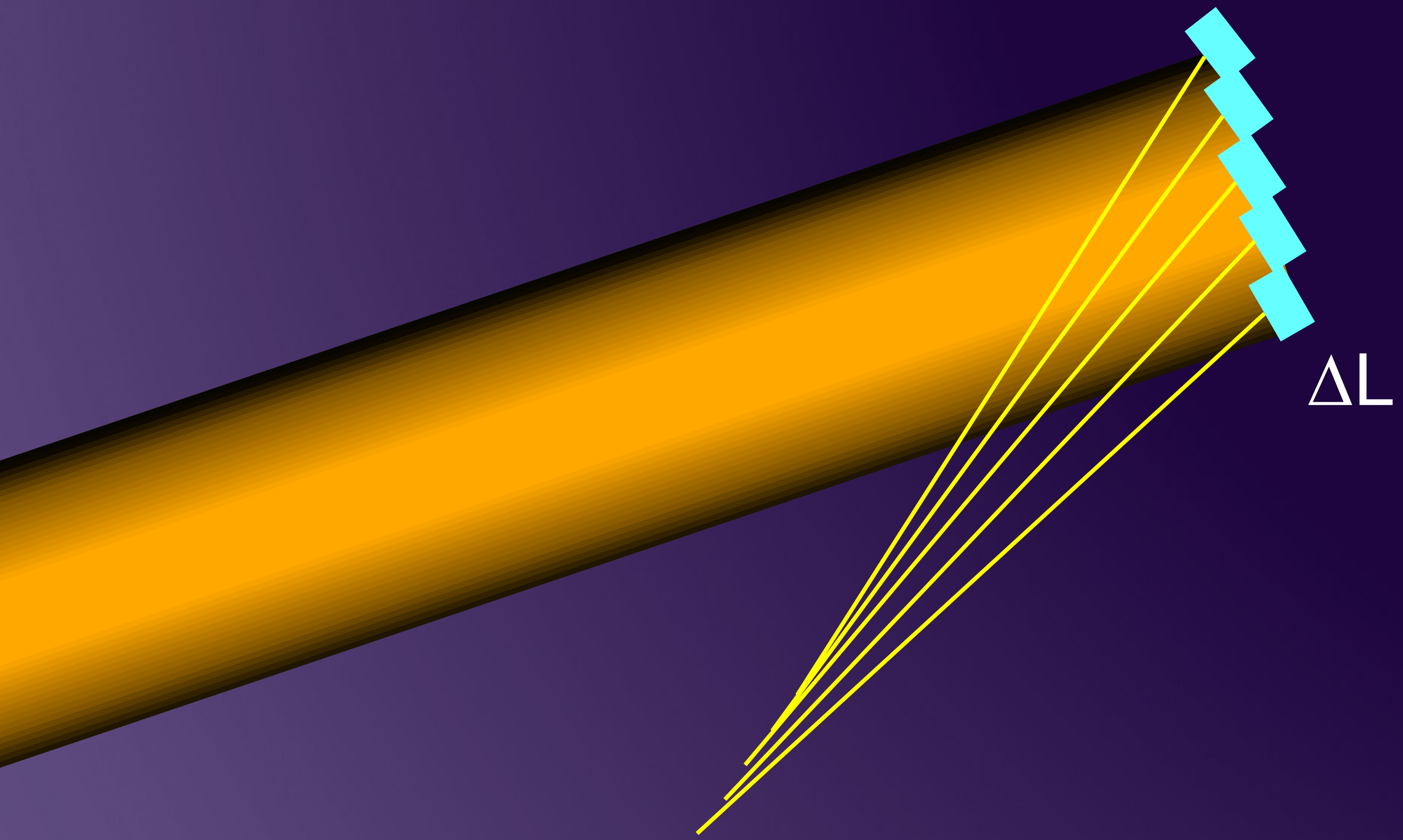
@ 0.55 NA 4x

50 modes 1D

L must be > 5m

HOE size > 140 mm

Temporal to spatial incoherence transformation is possible



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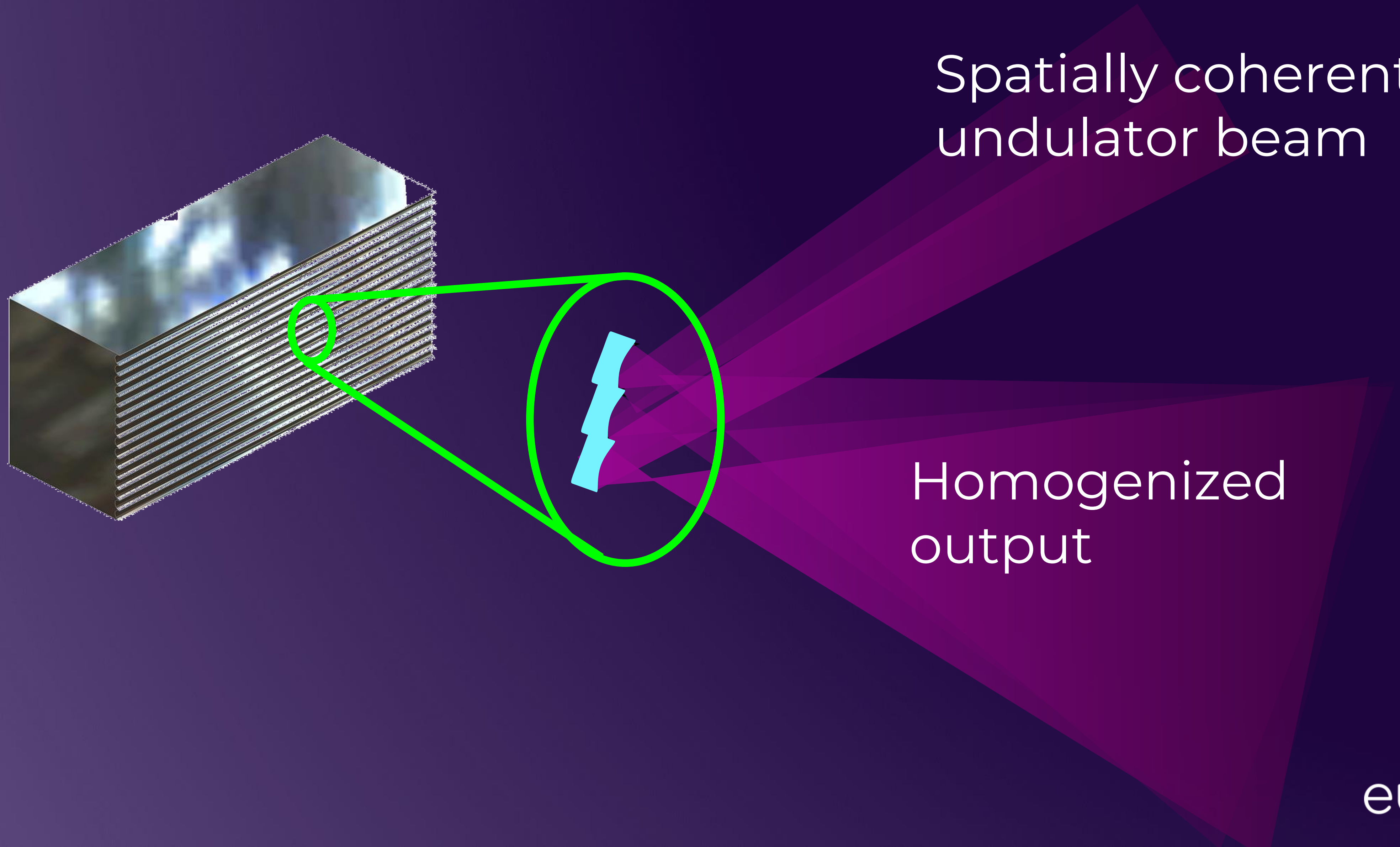
Fly-eye implementation on Berkeley MET



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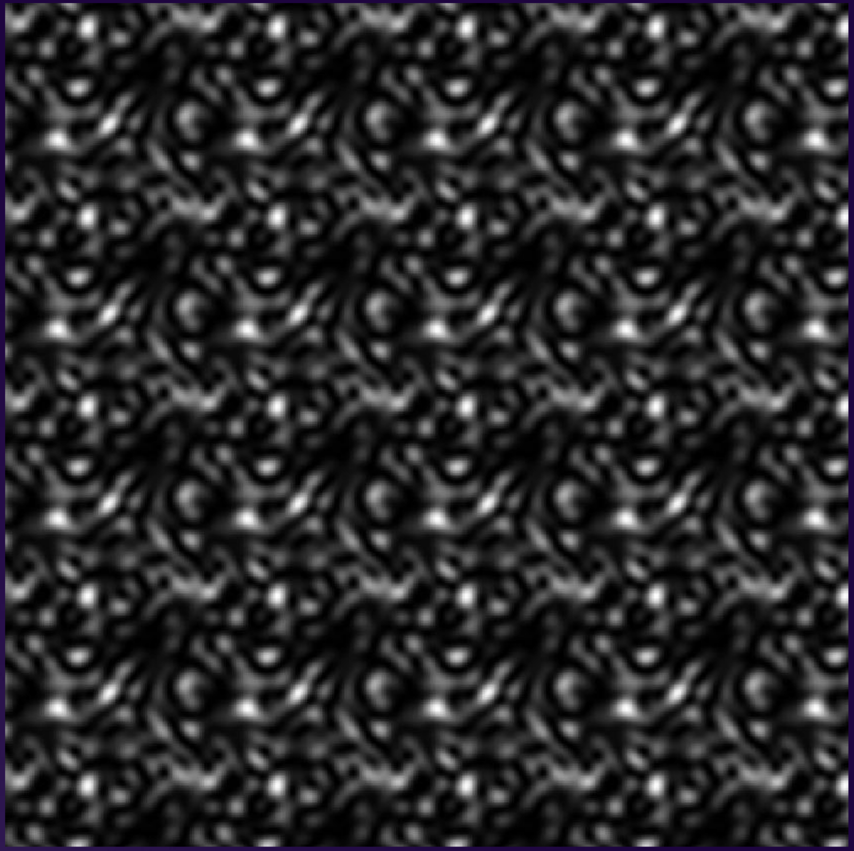
Fly-eye implementation on Berkeley MET

Achieved uniformity

Expected uniformity
with full coherence



100-channel 2D fly-eye, from Berkeley MET

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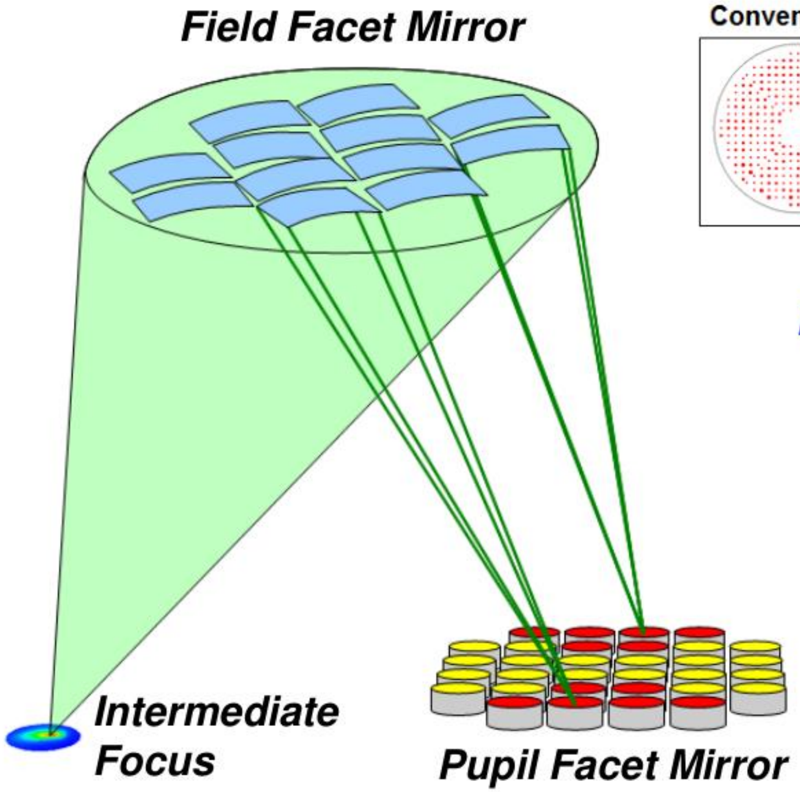
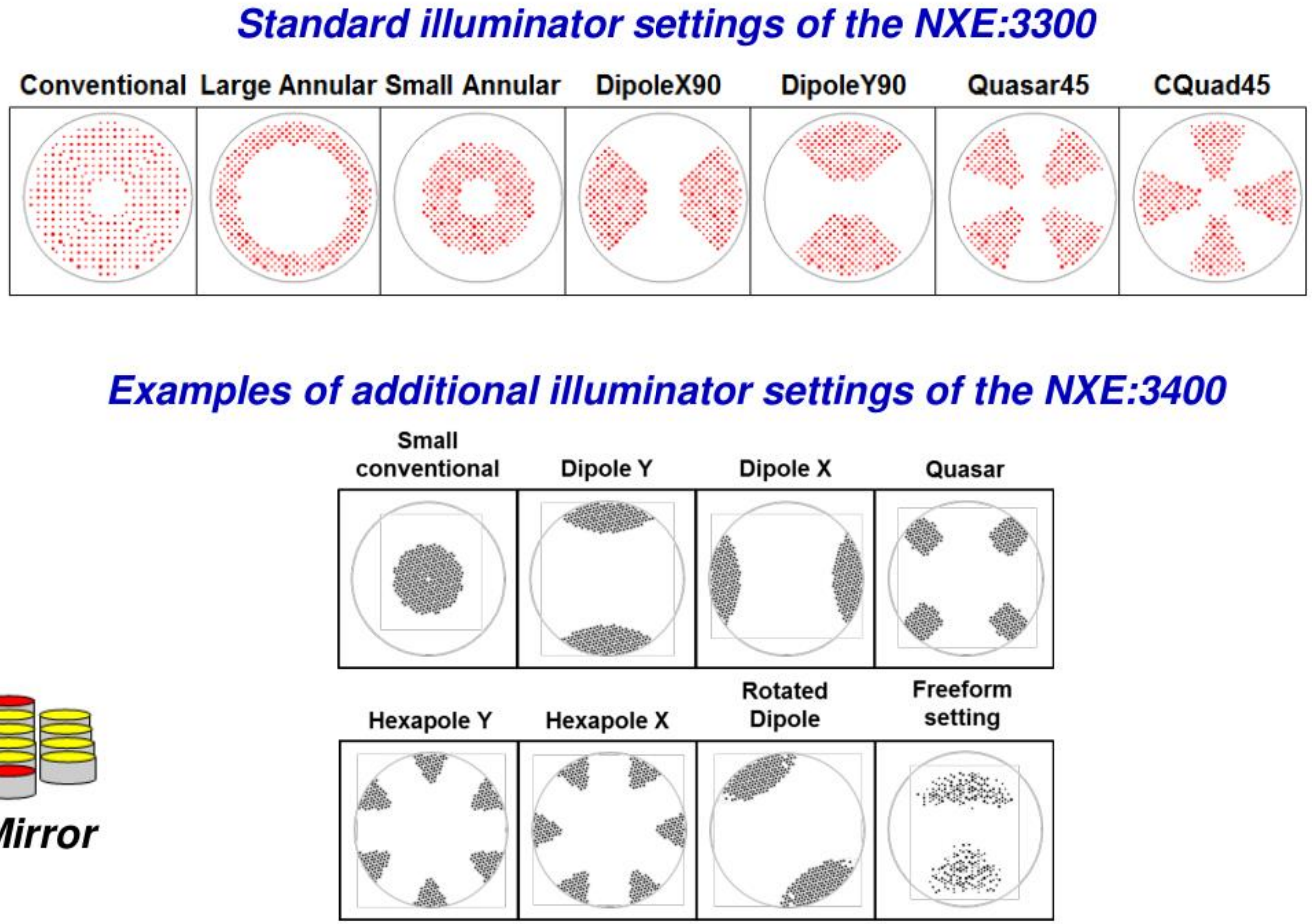
Starlith® 3400: Highly flexible illuminator

Allows lossless changes of settings and the optimization of image contrast.





Sascha Migura, 2019 EUVL Workshop

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Summary

- Coherence reduction is essential for accelerator-based lithography
- Lithography also benefits substantially from flexible coherence engineering
- High speed imaging and lithography applications render active coherence control methods ineffective
- “Broadband” FEL light enables passive coherence reduction by coupling temporal to spatial modes
- Passive coherence reduction readily incorporated into existing EUV lithography systems

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Thank You

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