High-resolution Penumbral Imaging on the NIF

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Lawrence Livermore National Laboratory

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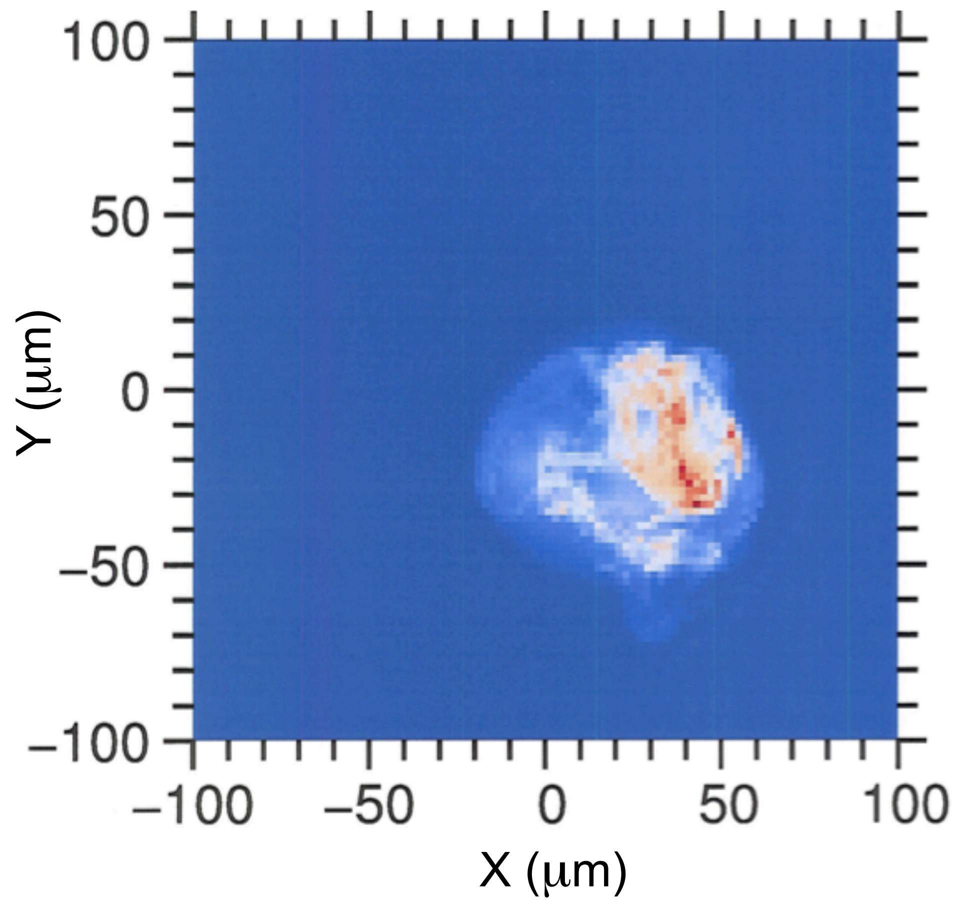
Motivation
high-res ICF-hotspot simulations show complex behavior

Simulated 3D hotspot

1 keV Tion
iso-surface

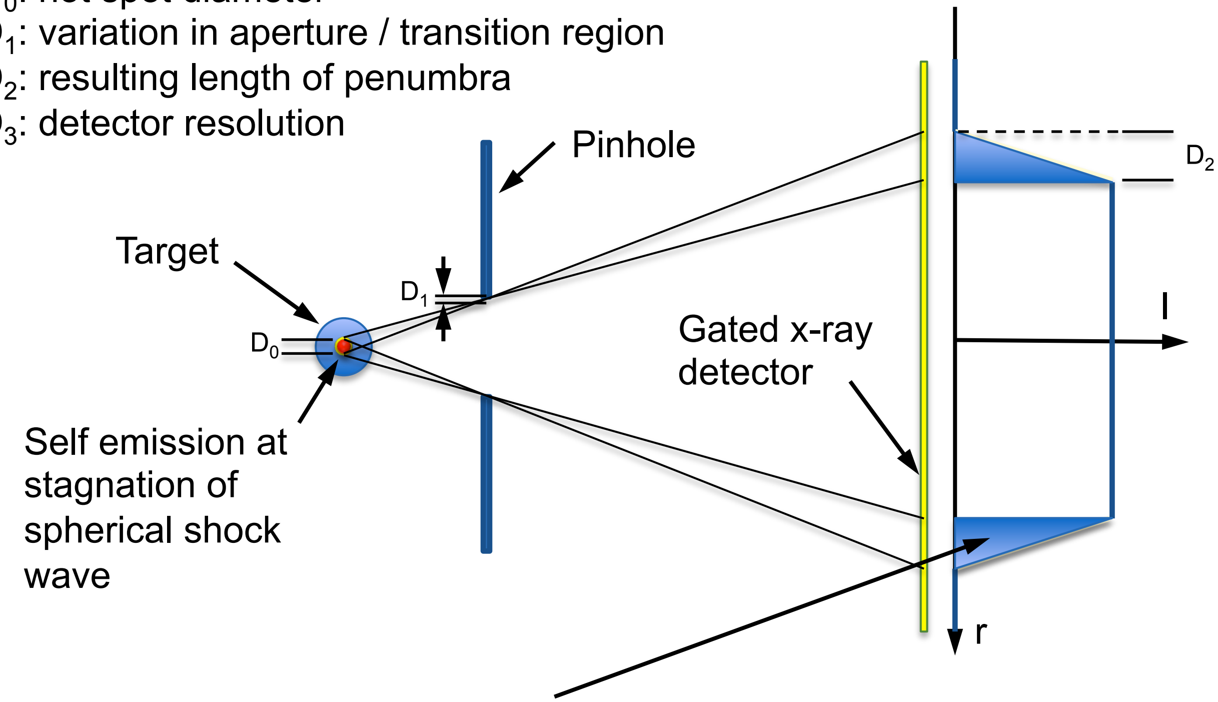
Simulated 2D hotspot image



Brian Spears & Dave Munro

Principle of Penumbral Imaging

D_0: hot spot diameter
D_1: variation in aperture / transition region
D_2: resulting length of penumbra
D_3: detector resolution



Penumbra
⇒ Spatial expansion and structure of self emitting plasma

Limiting factors:

Physical:

- **Diffraction** *(typically few μm in detector plane)*

Technical:

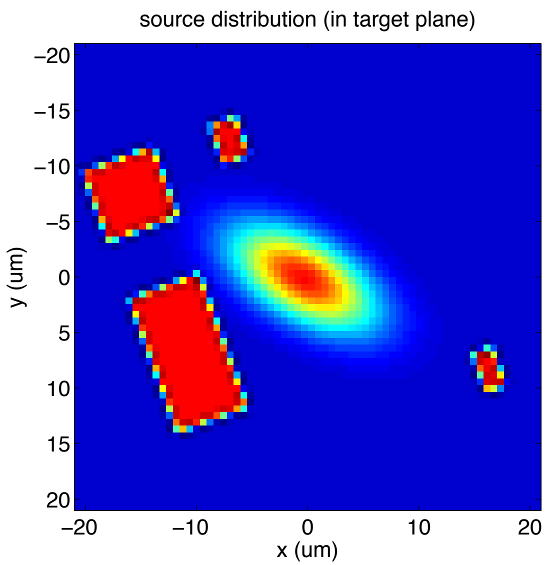
- **Magnification** *(15x PDIM, 15x 90-78, 58x DIXI IP, 64x DIXI)*
- **Detector resolution**: *IP: 90μm, GXD: ~40μm, DIXI: ~270μm*
- **'transparency' of tapered edge of Aperture** => *broadening of Penumbra (typically few μm in detector plane)*
- **Dynamic detector range, QE, photon yield and noise**

B. Bachmann, Rev. Sci. Instrum. **85**, 11D614 (2014)
D. Ress etal, Science 241, no. 4868, pp. 956-958 (1988)

Proof of Principle
First: Simulated 10μm Pinhole Imaging

Our “imaginary” setup:

- Pinhole radius: 10μm
- Magnification: 15x
- Detector resolution: GXD (9x9μm pixel size)



SOURCE
“PHANTOM”

Proof of Principle
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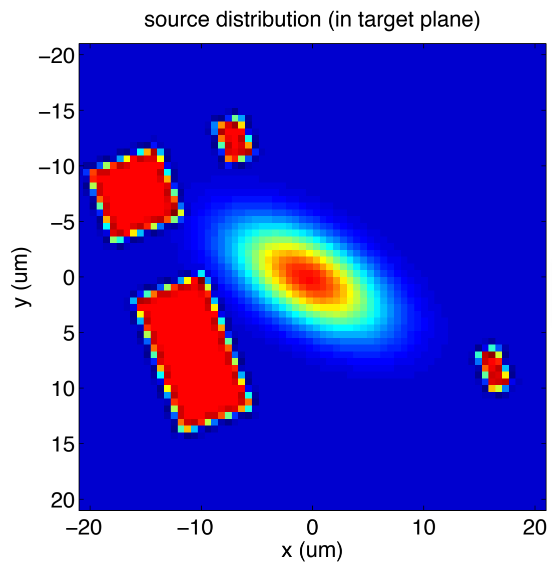
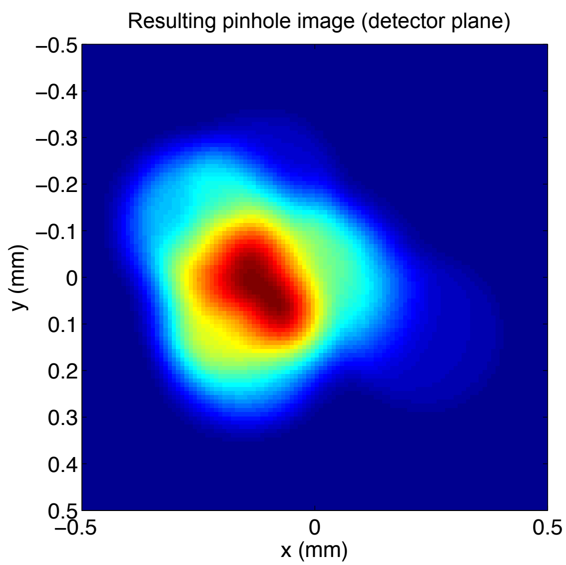


SOURCE
"PHANTOM"



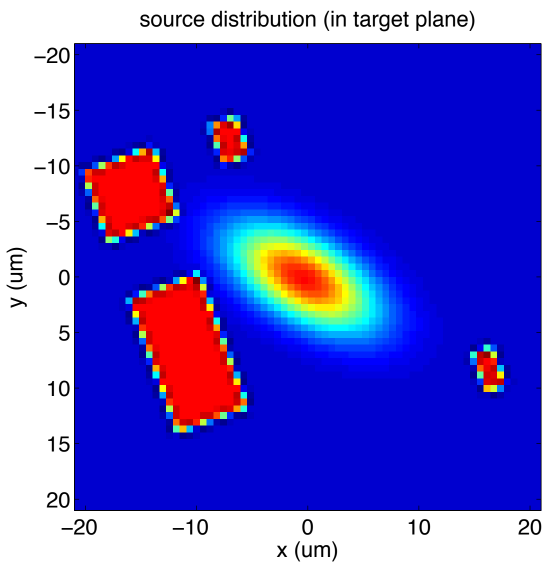
Pinhole Image
(raytrace)

That is what we would see with pinhole imaging

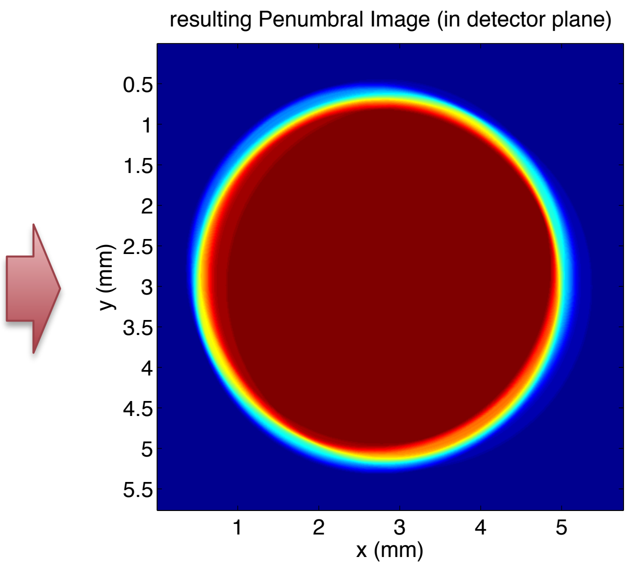
Proof of Principle
Now: Simulated Penumbral Imaging

Our "imaginary" setup:

- Pinhole radius: **140μm**
- Magnification: 15x
- Detector resolution: GXD (9x9μm pixel size)
- Smallest distinguishable object in source distribution:
  600nm = resulting best possible Penumbral Image Resolution with this setup
  (limited by detector resolution)



SOURCE
"PHANTOM"



Penumbral
Image

Proof of Principle
Simulated Penumbral Imaging

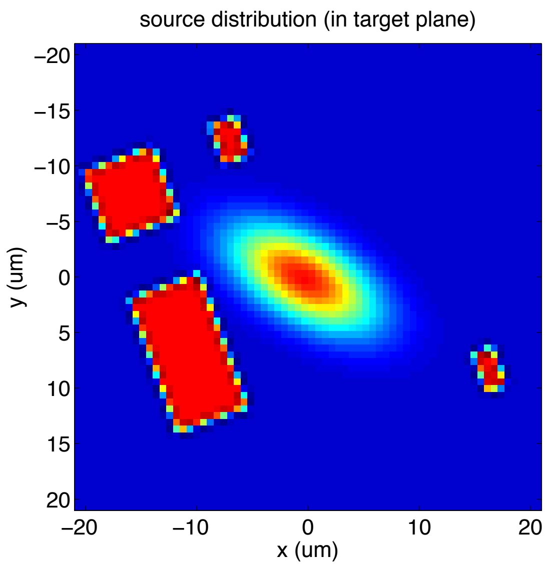
Our “imaginary” setup:

- Pinhole radius: **140μm**
- Magnification: 15x
- Detector resolution: GXD (9x9μm pixel size)
- Smallest distinguishable object in source distribution:

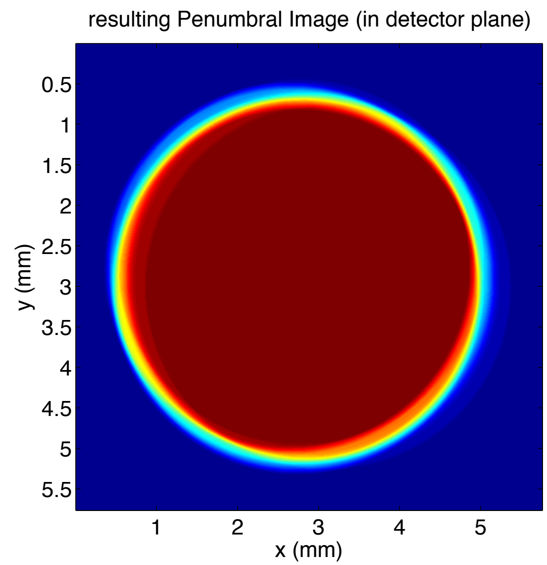
  600nm = resulting best possible Penumbral Image Resolution with this setup

  (limited by detector resolution)

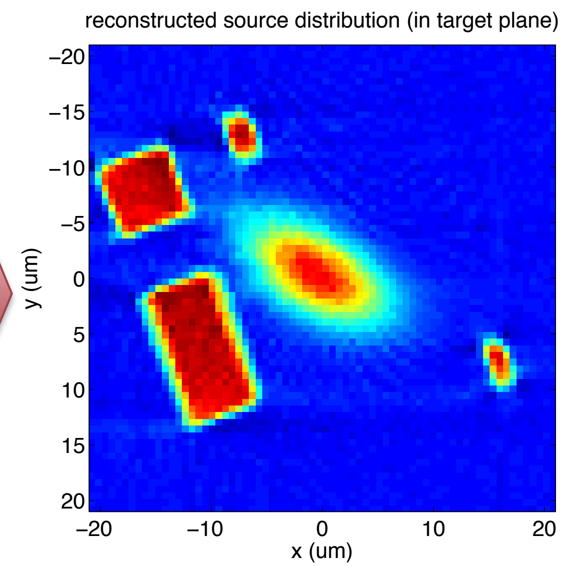
Inverse Radon transform



SOURCE
“PHANTOM”



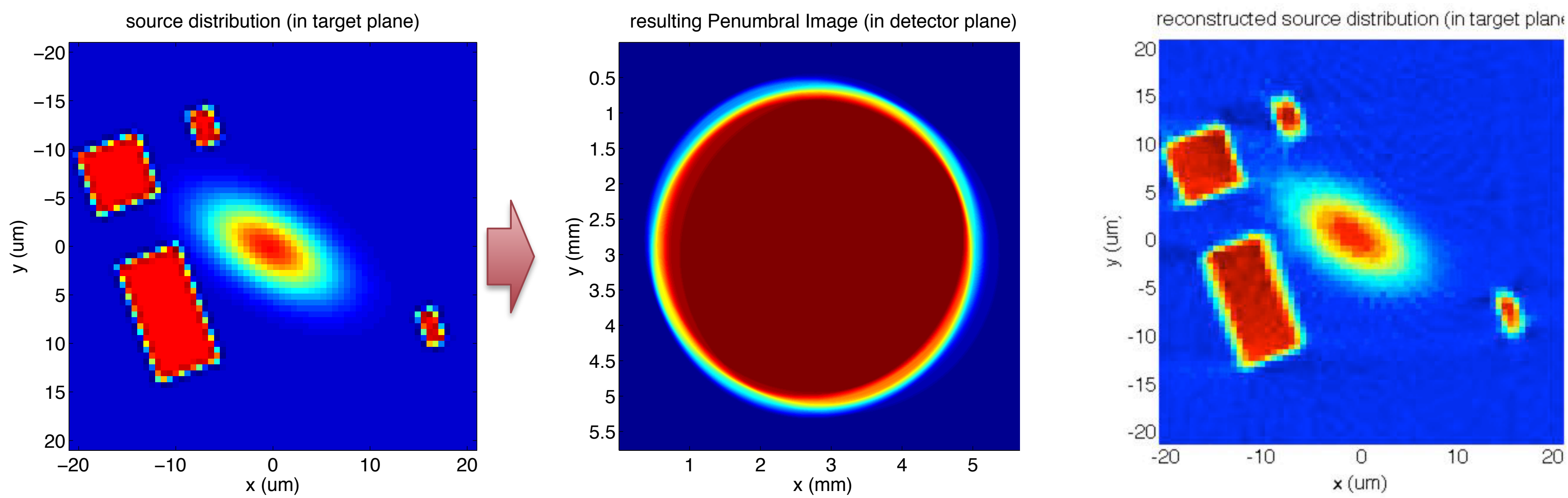
Penumbral
Image



RECONSTRUCTED

Proof of Principle
reconstruction visualization

Reconstruction by inverse Radon transformation



SOURCE
"PHANTOM"

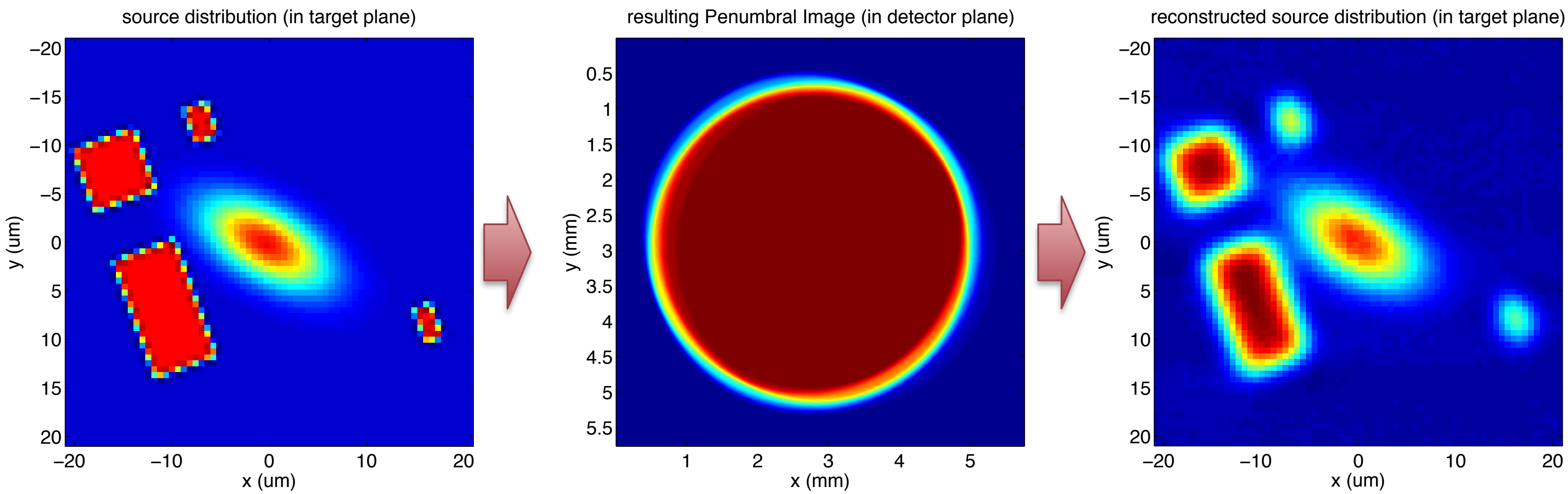
Penumbral
Image

RECONSTRUCTION

Proof of Principle
GXD point spread function added

Still working on including a more realistic point spread function and noise model for the GXD's

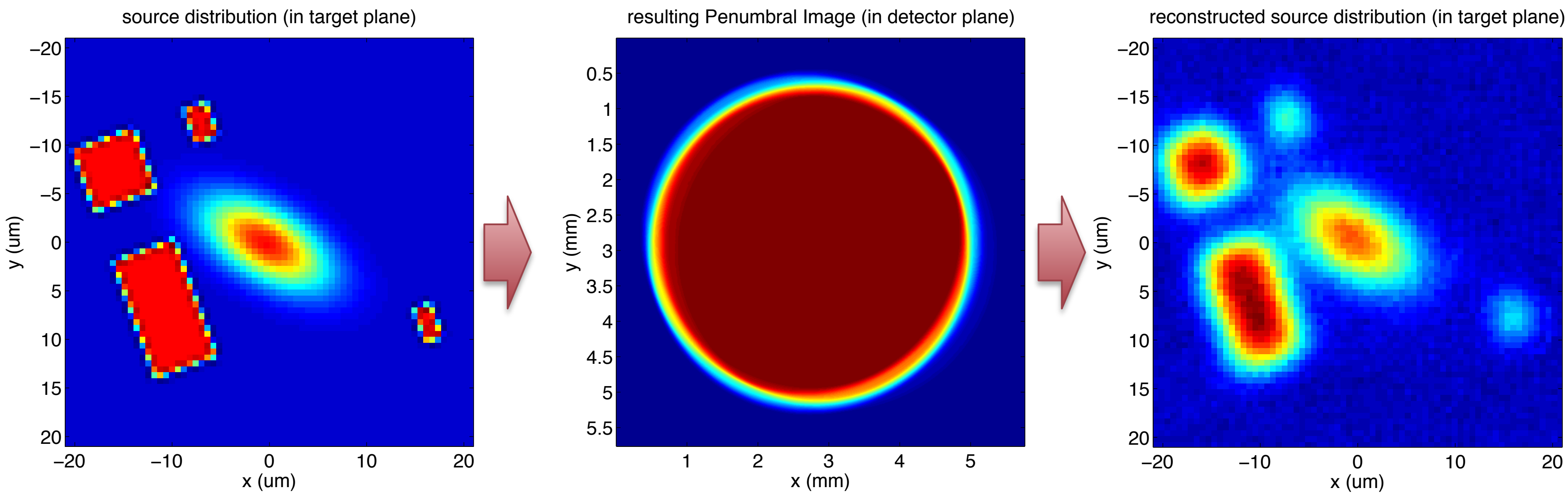
For now: 40μm FWHM 2D-Gauss:



SOURCE "PHANTOM" | Penumbral Image | RECONSTRUCTED

Proof of Principle
additional noise added

We expect noise to scale like sqrt(Signal):
Signal: 600 counts
Noise at max signal: 25 counts

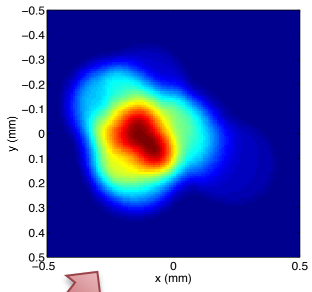


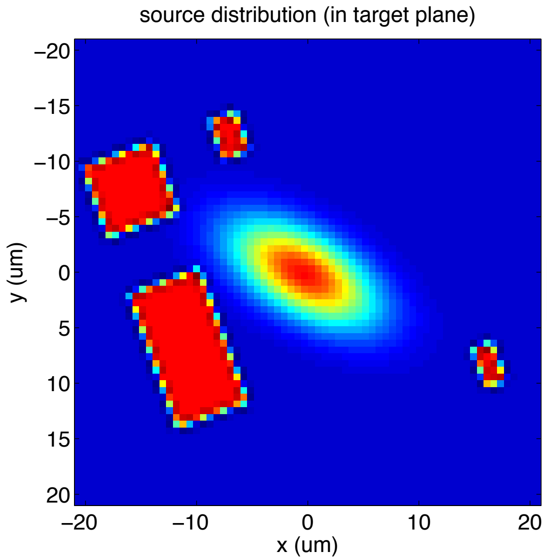
SOURCE "PHANTOM" | Penumbral Image | RECONSTRUCTED

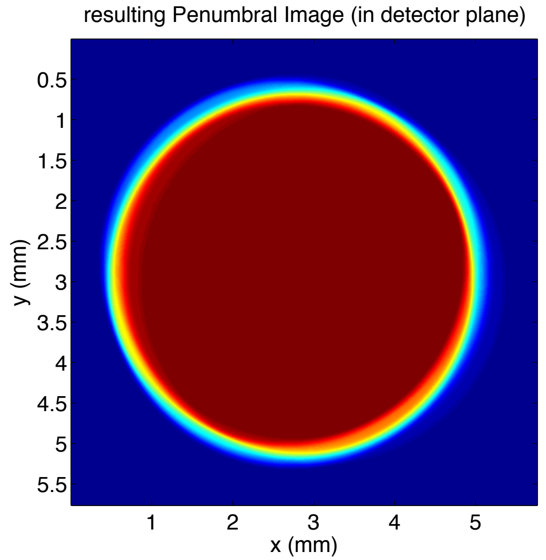
Proof of Principle
additional noise added

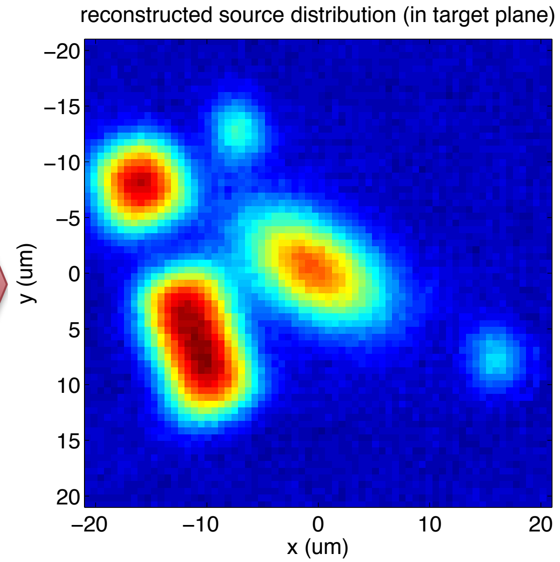
We expect noise to scale like sqrt(Signal):
Signal: 600 counts
Noise at max signal: 25 counts

10μm radius Pinhole image









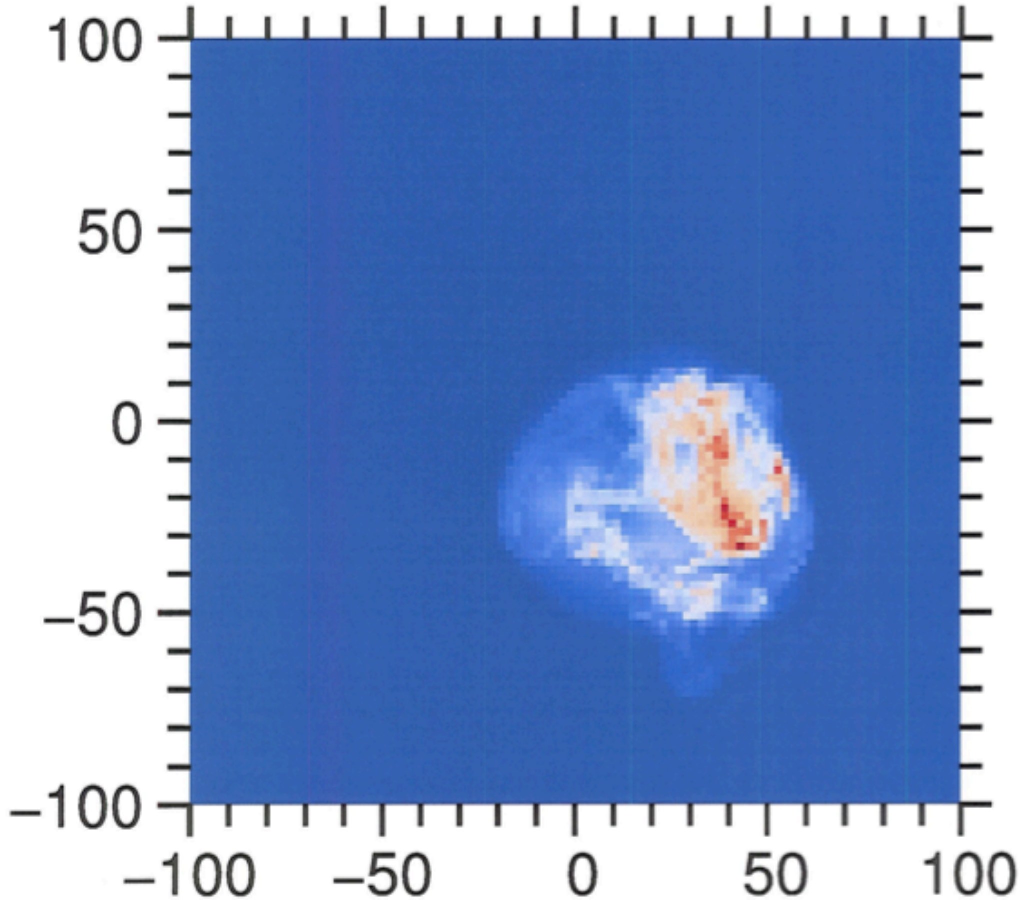
SOURCE "PHANTOM"

Penumbral Image

RECONSTRUCTED

High-resolution imaging of complex hotspot

Simulated hotspot emission with mix



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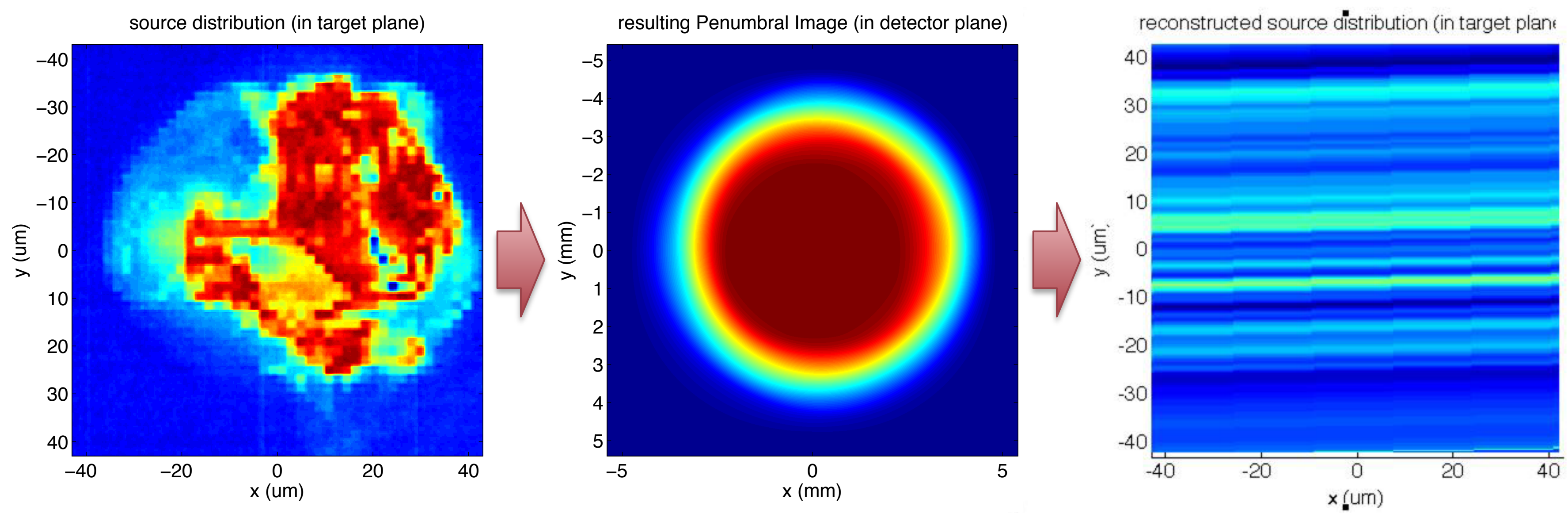
Reconstruction of a simulated complex hotspot Penumbral Image

Setup:

- Magnification: 31x
- Pinhole diameter: 220μm
- Noise: sqrt(Signal)
- GXD-Point Spread Function: 40μm FWHM Gauss
- Low dynamic range in source

Promising, but more work to do



SOURCE
Simulated complex hotspot

Penumbral
Image

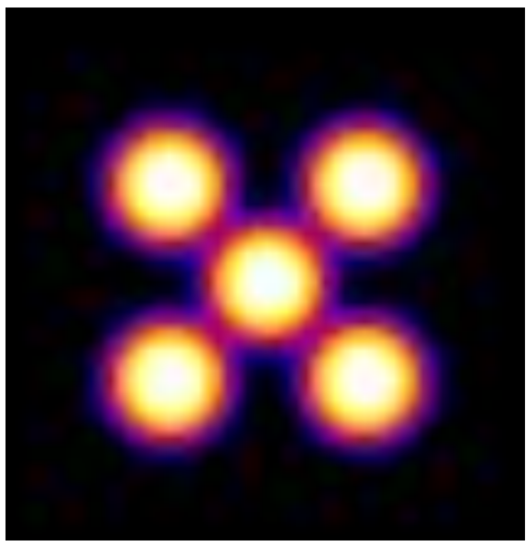
RECONSTRUCTION

Can we use DIXI for Penumbral Imaging?

Setup:

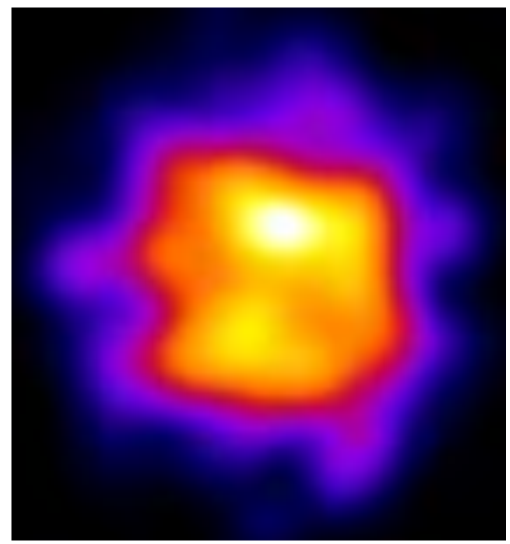
- Source-aperture distance: 100mm
- Aperture-Detector distance: 6400mm
- Detector resolution: ~270um

Source for DIXI



7μm

DIXI 10μm pinhole image



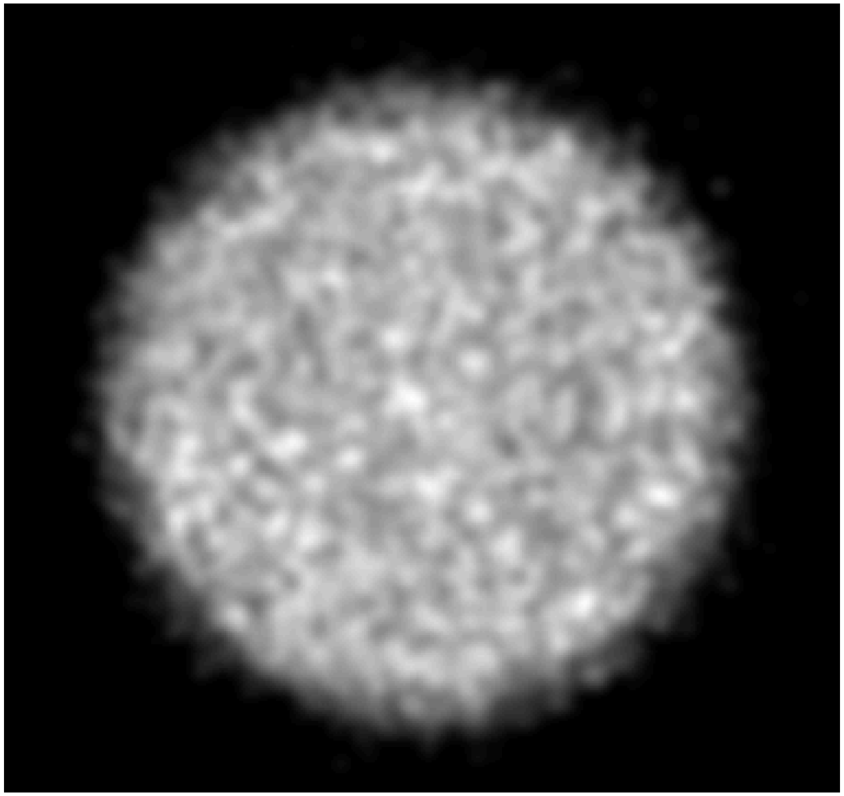
Taking into account all known image degradation effects

Simulated Penumbral Image by Terry Hilsabeck

Simulated Penumbral Image with DIXI 'setup'

Setup:

- Aperture diameter: 100μm
- Source-aperture distance: 100mm
- Aperture-Detector distance: 6400mm
- Detector resolution: ~270um

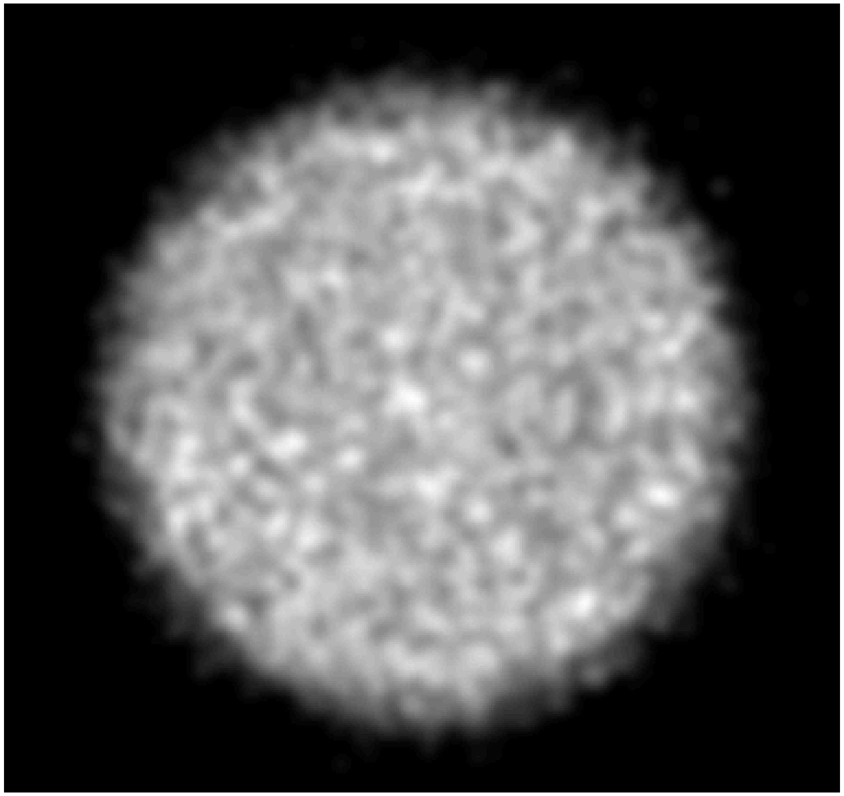


Simulated Penumbral Image by Terry Hilsabeck

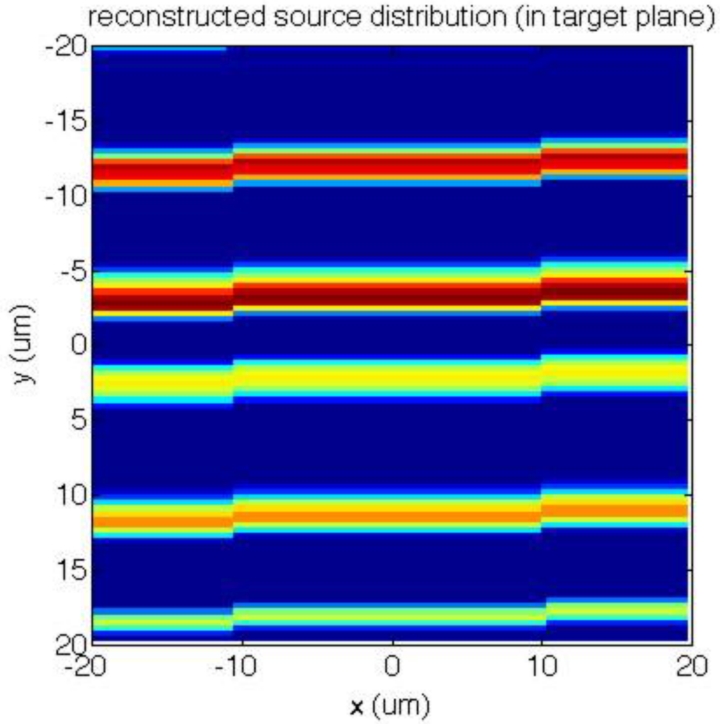
Reconstruction of simulated Penumbral Image with DIXI ‘setup’

Setup:

- Aperture diameter: 100μm
- Source-aperture distance: 100mm
- Aperture-Detector distance: 6400mm
- Detector resolution: ~270um



Simulated Penumbral Image by Terry Hilsabeck



Reconstruction of simulated Penumbral Image with DIXI 'setup'

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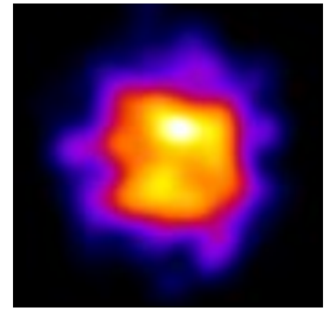
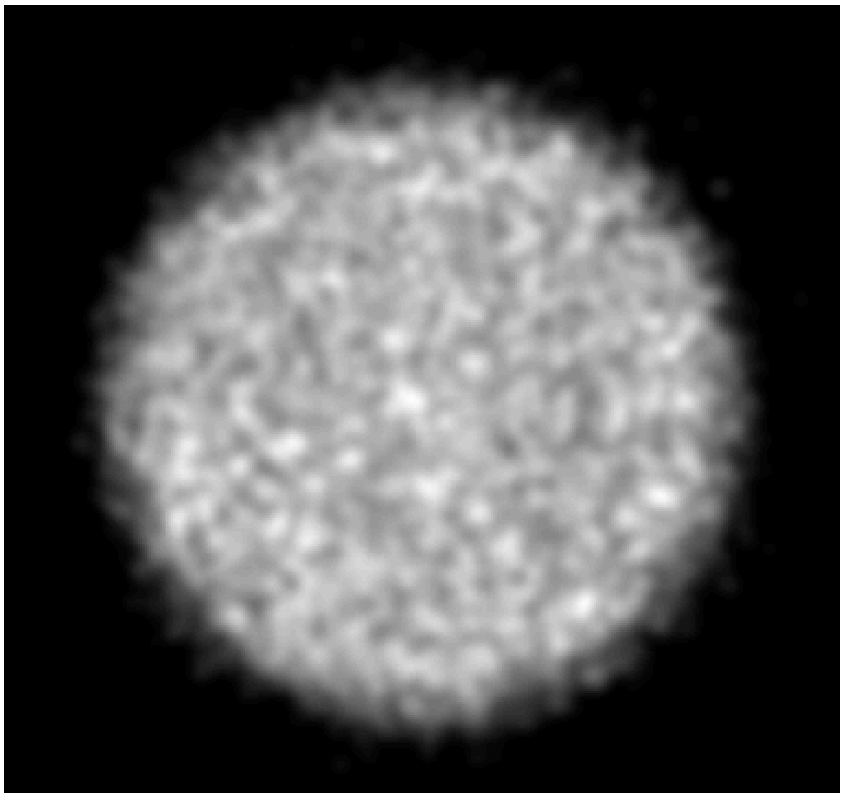
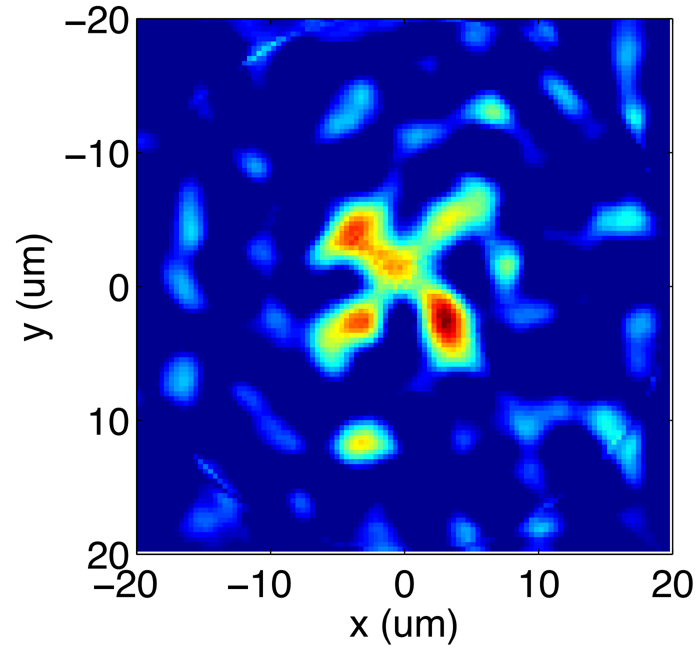


⇒ Limited mainly by pinhole size



Simulated Penumbral Image by Terry Hilsabeck

reconstructed source (in target plane)

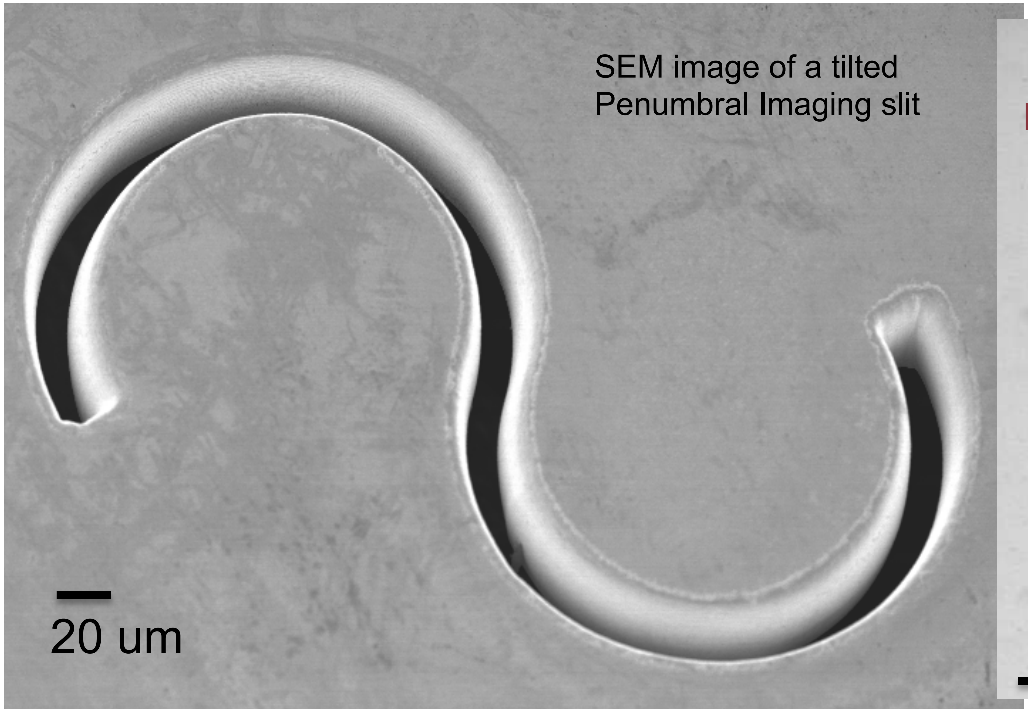


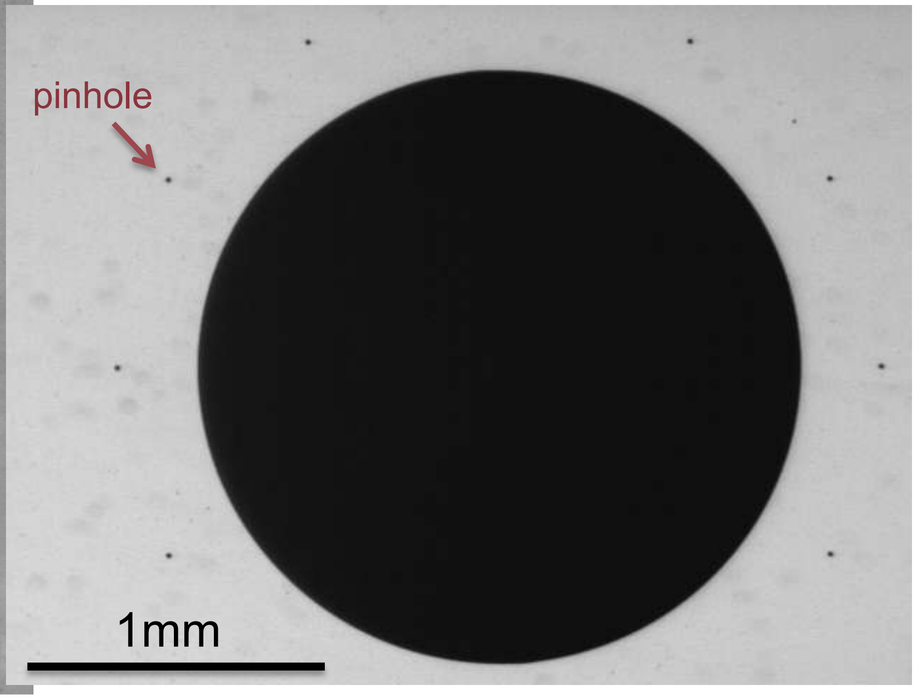
⇒ Limited mainly by detector resolution
(4μm in target plane)

GA can manufacture high-quality coded apertures that meet the criteria for Penumbral Imaging

High edge-quality s-shaped slit laser-cut by GA

Circular large area Penumbral Pinhole produced by GA (EDM + laser finished)





For ‘small objects’

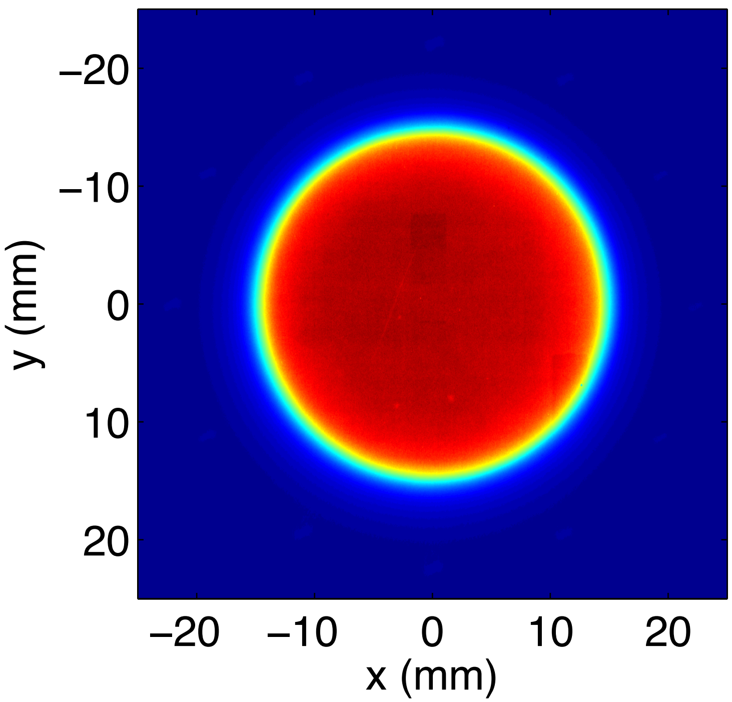
For ‘large objects’

We successfully demonstrated Penumbral Imaging on the NIF – on IP (15x Magnification)

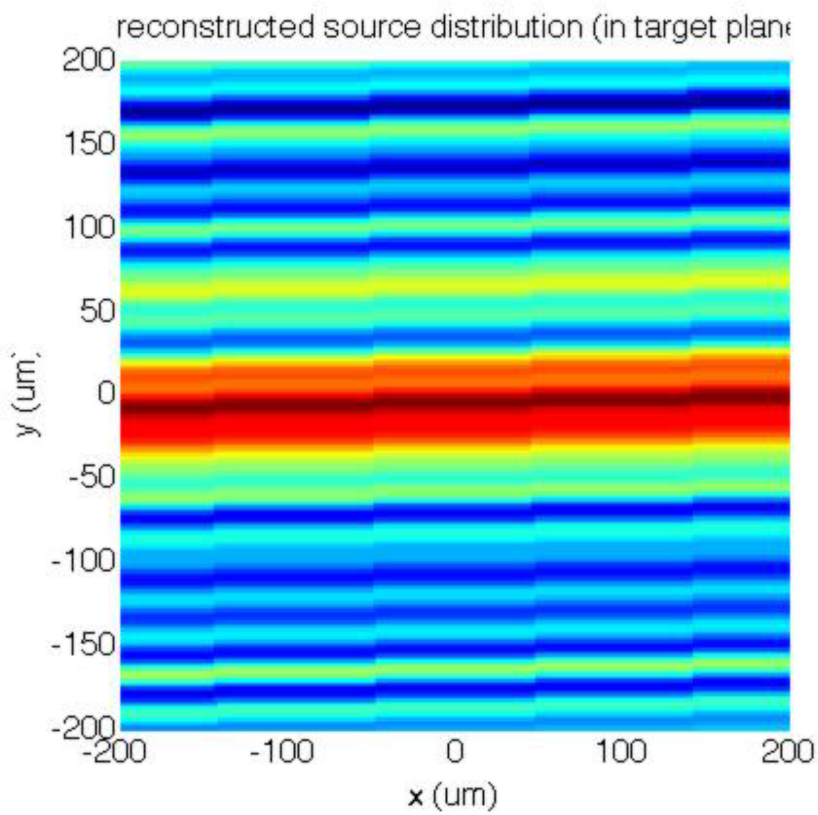
setup:
- Pinhole diameter: 2mm
- Magnification: 15x
- Detector: Image plate

Spatial resolution:
Limited by: Image Plate
Resolution: 90μm/15=6μm
⇒ M up => Resolution up

Penumbral Image (in detector plane)



Penumbral Image



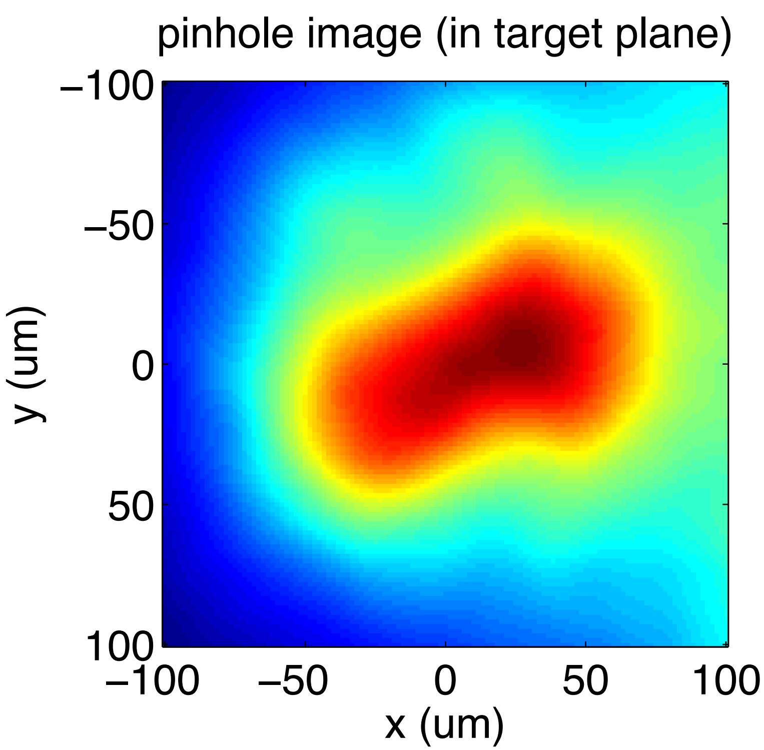
Play
Video

Reconstruction

We successfully demonstrated Penumbral Imaging on the NIF – on IP (15x Magnification)

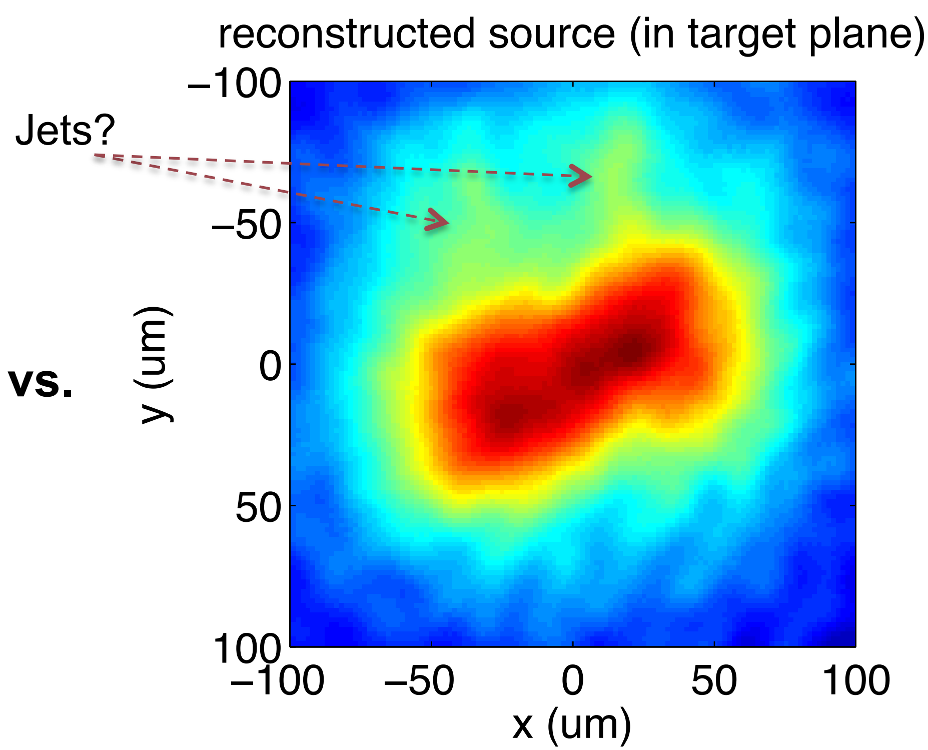
setup:
- Pinhole diameter: 25μm
- Magnification: 15x
- Detector: Image plate
- Spatial resolution: 27μm

setup:
- Pinhole diameter: 2mm
- Magnification: 15x
- Detector: Image plate
- Spatial resolution: 6μm



Pinhole Image

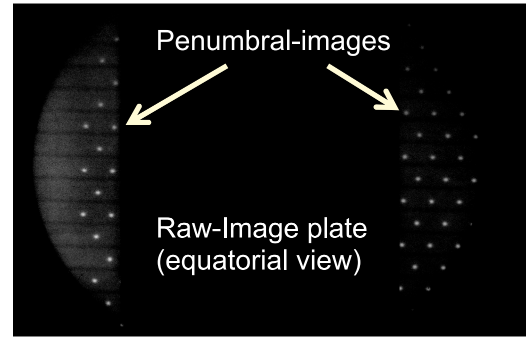
vs.



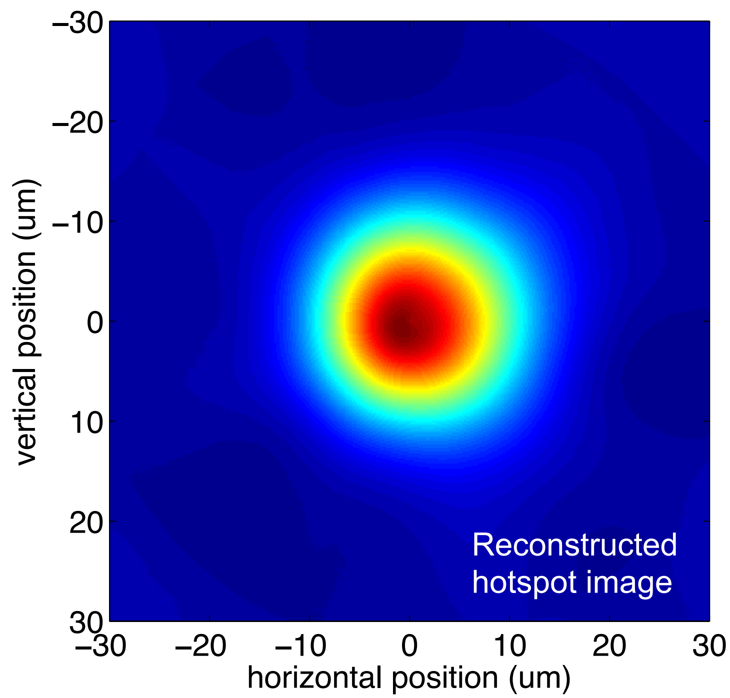
Reconstructed Penumbral Image
(additional blurring yields pinhole image)

We successfully fielded Penumbral Imaging on the NIF – on IP (58x Magnification)

Gbar solid sphere target, on Image Plate of DIXI LoS:



Reconstruction



10 μm radius (1/e)

Highest resolution hotspot image on the NIF to date: <u>1.5μm resolution (limited by IP resolution)</u>

Summary

- 1.5μm resolution Penumbral Imaging has been successfully fielded on the NIF

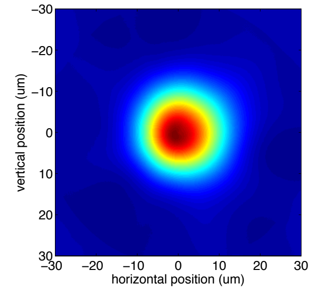
- Penumbral imaging has potential of significantly improving hotspot imaging in ICF implosions

- Manufacturing challenges of quality apertures have been overcome

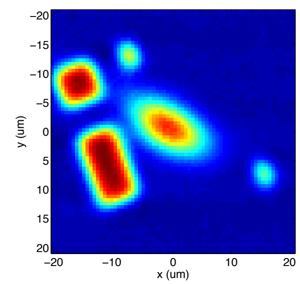
- Many possible applications

"we just scratched the surface"

Reconstructed Penumbral Image
N140928-004

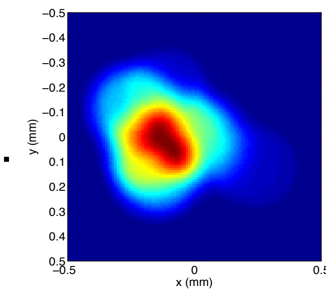


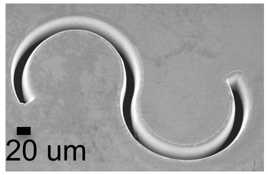
Penumbral Imaging



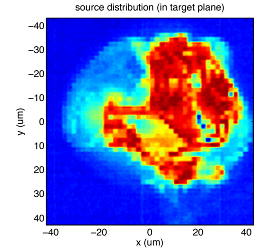
vs.

Pinhole Imaging

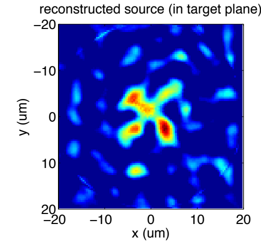




source distribution (in target plane)



reconstructed source (in target plane)

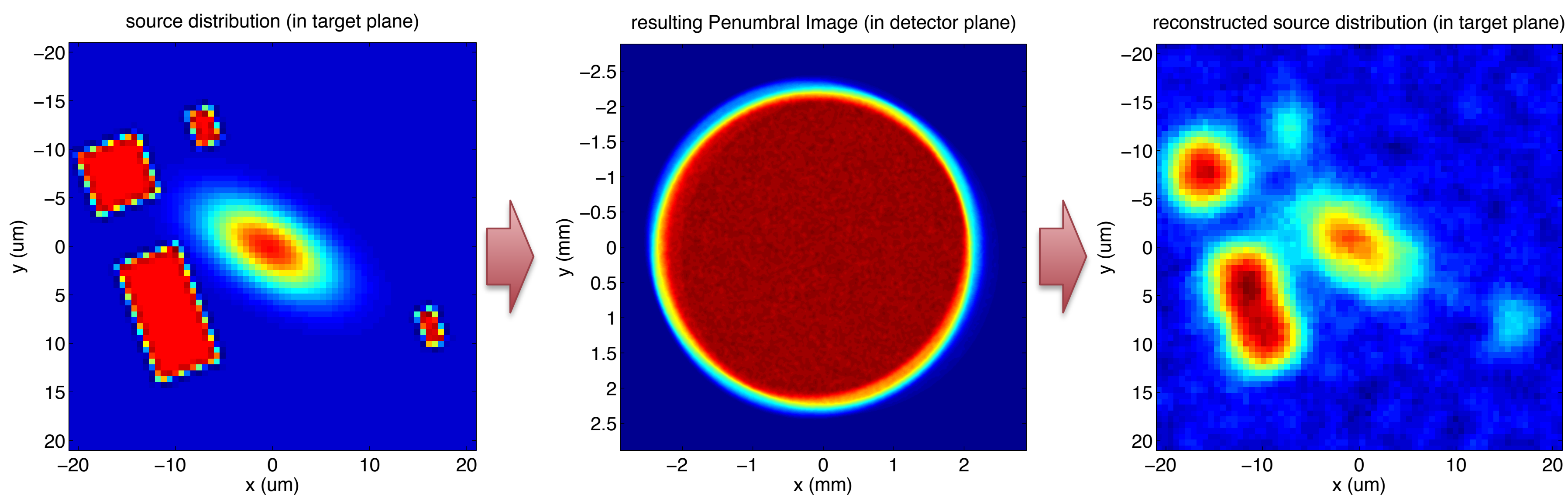



NIF

Backup

Proof of Principle
5 times more noise added (than one would expect)

Noise=5*sqrt(Signal):
Signal: 600 counts
Noise at max signal: 125 counts



SOURCE
“PHANTOM”

Penumbral
Image

RECONSTRUCTED

Proof of Principle
skewing the penumbral image

Skewing operation:

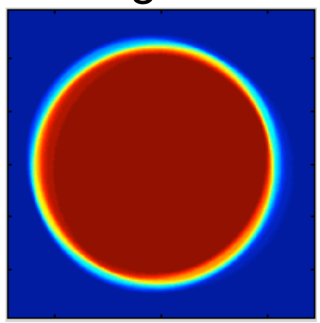
Resample Grid-coordinates:

$$A = \begin{bmatrix} 1+u1 & u2 \\ u3 & 1+u4 \end{bmatrix}$$

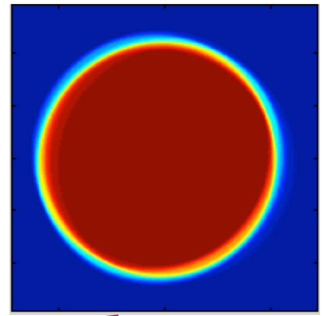
$$B = \begin{bmatrix} u5 \\ u6 \end{bmatrix}$$

$$\begin{bmatrix} x^* \\ y^* \end{bmatrix} = A \begin{bmatrix} x \\ y \end{bmatrix} + B;$$

original

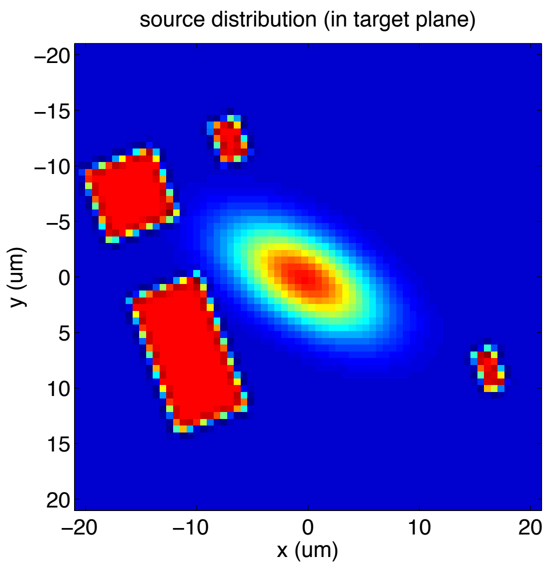


skewed

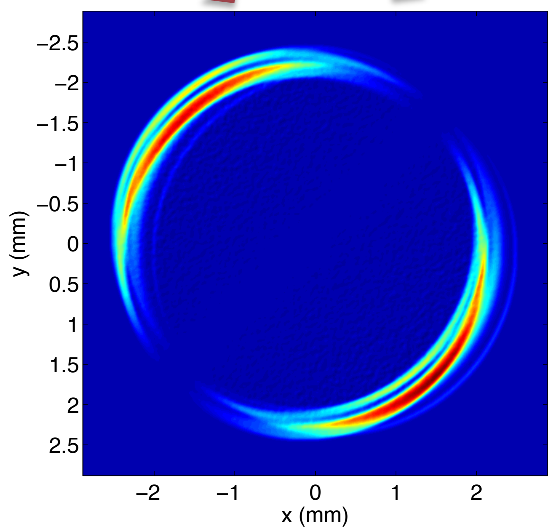


This results in a
- Shift
- Scale
- Rotation
- Anisotropy

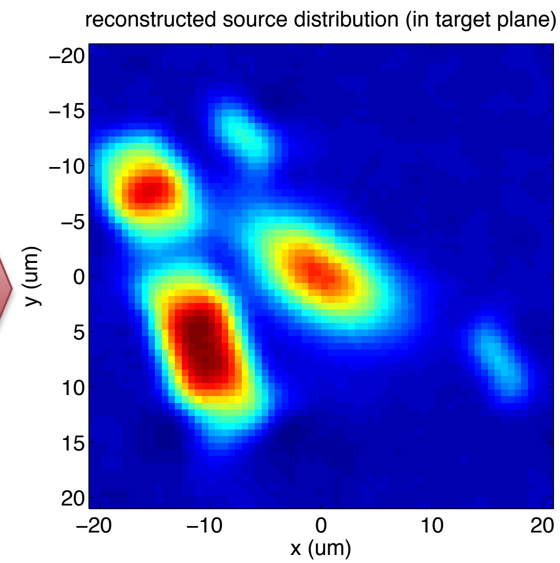
of the penumbral image



SOURCE
"PHANTOM"



Differences
Original-Skewed

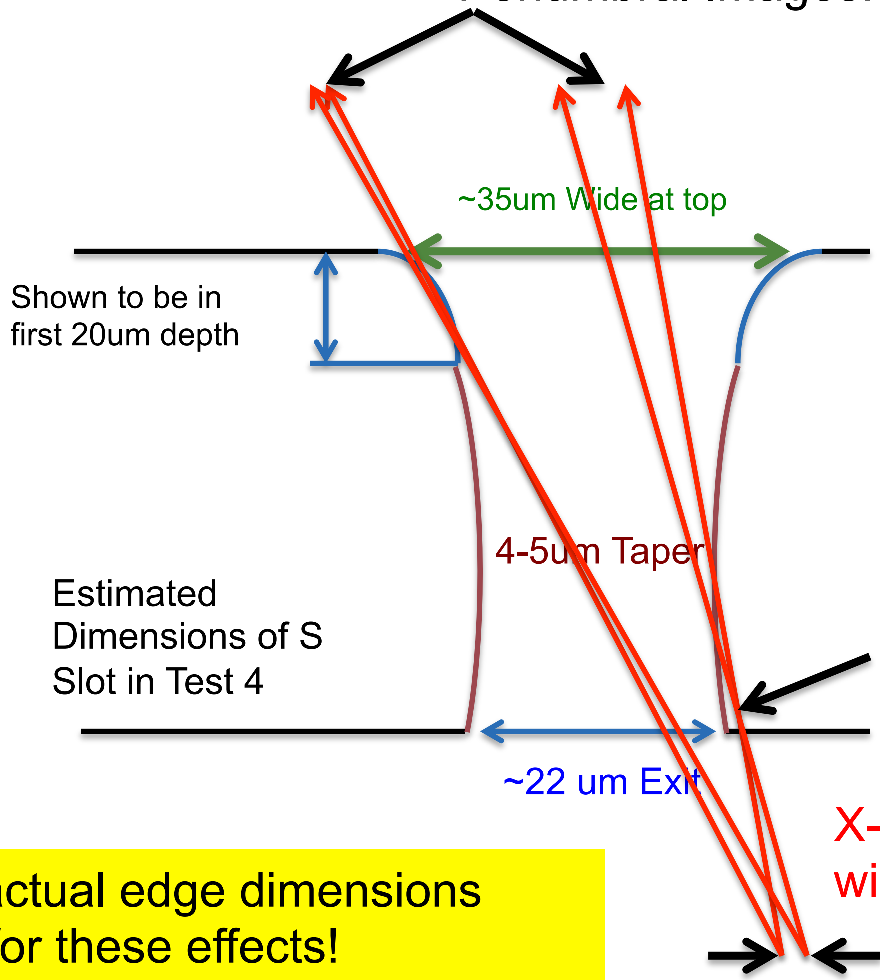


RECONSTRUCTED

The role of the 'edge'

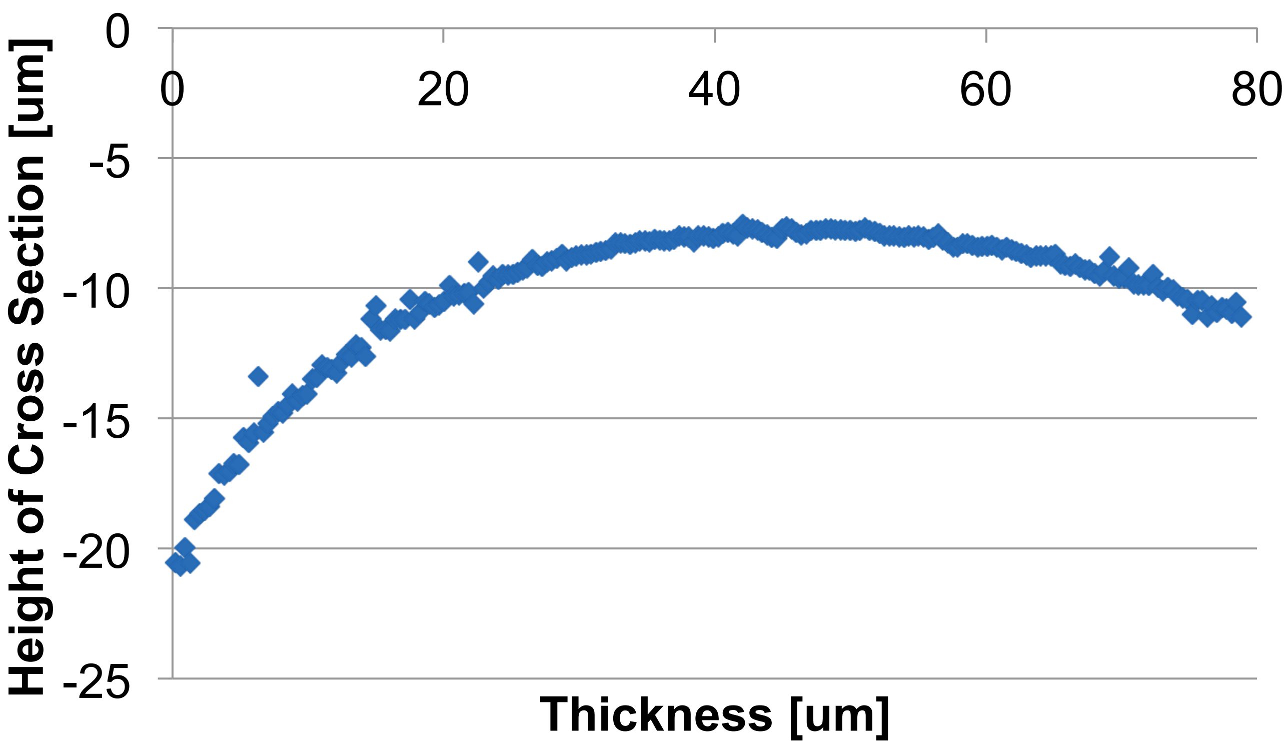
While the previously shown deconvolution with a contact radiograph gives approximate information of how the x-rays pass through the slit, e.g. a 3D ray tracing can capture the whole process:

Penumbral Images: the width of the Penumbral Images depends on the size of the Hotspot as well as the x-ray attenuation along the tapered edge



=> Knowledge of actual edge dimensions allows to account for these effects!

Test 4 White Light Interferometer Cross Section (Trial 4)




NIF