High-resolution Penumbral Imaging on the NIF

October 6, 2015

Benjamin Bachmann
Motivation

high-res ICF-hotspot simulations show complex behavior

Simulated 3D hotspot

Simulated 2D hotspot image

1 keV Tion iso-surface

Brian Spears & Dave Munro
Principle of Penumbral Imaging

D₀: hot spot diameter
D₁: variation in aperture / transition region
D₂: resulting length of penumbra
D₃: detector resolution

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

Proof of Principle
First: Simulated 10μm Pinhole Imaging

Our “imaginary” setup:
- Pinhole radius: 10μm
- Magnification: 15x
- Detector resolution: GXD (9x9μm pixel size)

source distribution (in target plane)

SOURCE
“PHANTOM”
Proof of Principle
First: Simulated 10μm Pinhole Imaging

Our “imaginary” setup:
- Pinhole radius: 10μm
- Magnification: 15x
- Detector resolution: GXD (9x9μm pixel size)

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)
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)

SOURCE
“PHANTOM”

Penumbral
Image

RECONSTRUCTED

Inverse Radon transform
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 $\sqrt{\text{Signal}}$:
Signal: 600 counts
Noise at max signal: 25 counts

SOURCE
“PHANTOM”

Penumbral Image

RECONSTRUCTED

10µm radius Pinhole image
High-resolution imaging of complex hotspot

Simulated hotspot emission with mix

Brian Spears & Dave Munro
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
Can we use DIXI for Penumbral Imaging?

Setup:
• Source-aperture distance: 100mm
• Aperture-Detector distance: 6400mm
• Detector resolution: ~270µm

Source for DIXI → 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’

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

⇒ Limited mainly by pinhole size
⇒ 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: $90\mu m/15=6\mu m$
$\Rightarrow M\uparrow \Rightarrow \text{Resolution up}$

![Penumbral Image](image1)

![Reconstruction](image2)
We successfully demonstrated Penumbral Imaging on the NIF – on IP (15x Magnification)

setup:
- Pinhole diameter: 25\(\mu\)m
- Magnification: 15x
- Detector: Image plate
- Spatial resolution: 27\(\mu\)m

setup:
- Pinhole diameter: 2mm
- Magnification: 15x
- Detector: Image plate
- Spatial resolution: 6\(\mu\)m

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:

10 µm radius (1/e)

Highest resolution hotspot image on the NIF to date: 1.5µm resolution (limited by IP resolution)
Summary

- 1.5 µm 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”
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
Proof of Principle
skewing the penumbral image

Skewing operation:
Resample Grid-coordinates:
\[
A = \begin{bmatrix}
1+u1 & u2 \\
u3 & 1+u4
\end{bmatrix}
\]
\[
B = \begin{bmatrix}
u5 \\
u6
\end{bmatrix}
\]
\[
\begin{bmatrix}
x^* \\
y^*
\end{bmatrix} = A \begin{bmatrix}
x \\
y
\end{bmatrix} + B;
\]

This results in a
- Shift
- Scale
- Rotation
- Anisotropy
of the penumbral image

source distribution (in target plane)
original
skewed
reconstructed source distribution (in target plane)

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:

- **4-5um Taper**
- **~35um Wide at top**
- **~22 um Exit**

Shown to be in first 20um depth

**Estimated Dimensions of S Slot in Test 4**

**Partly transmission through material**

**X-rays from Hotspot with size $D_0$**

**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)