Simulation and development of a coded source neutron imaging system

Accelerator and Detector Research and Development Program Principal Investigators' 2011 meeting

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and Hector Santos-Villalobos,
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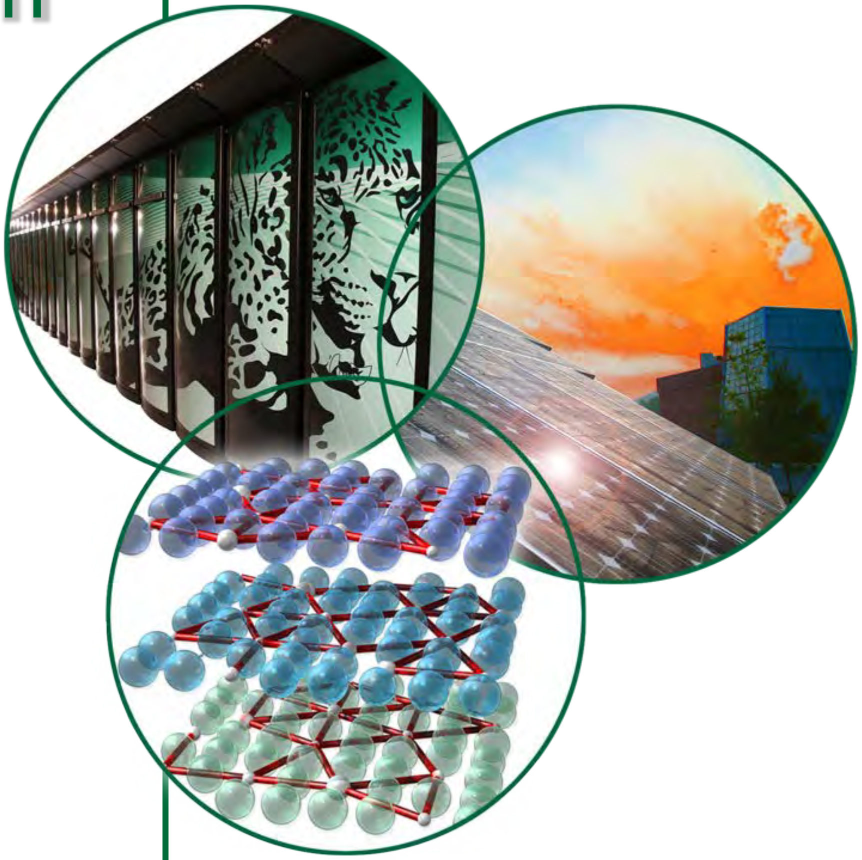

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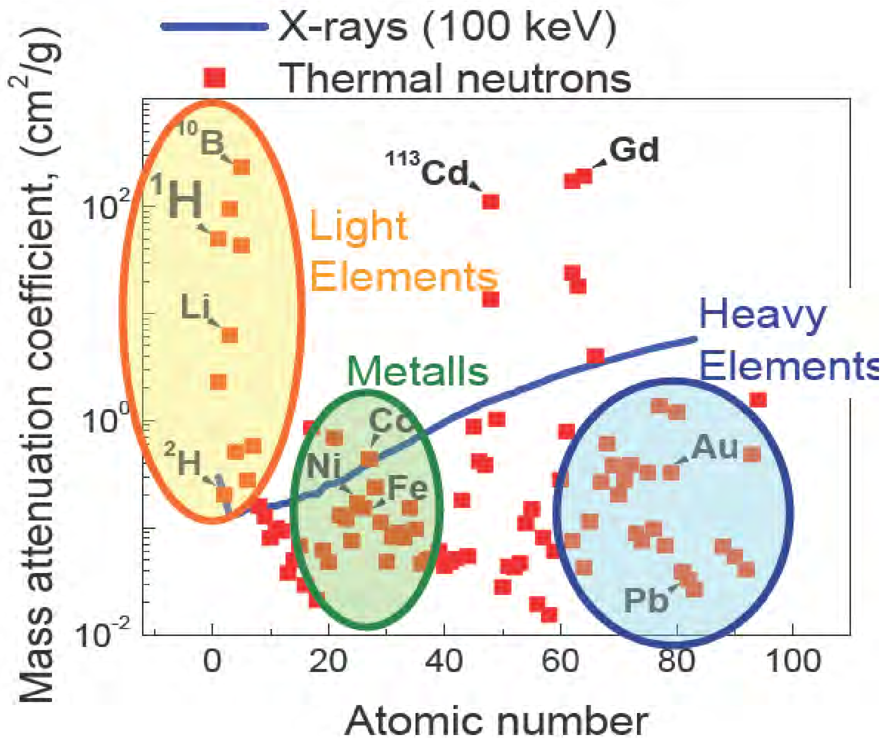
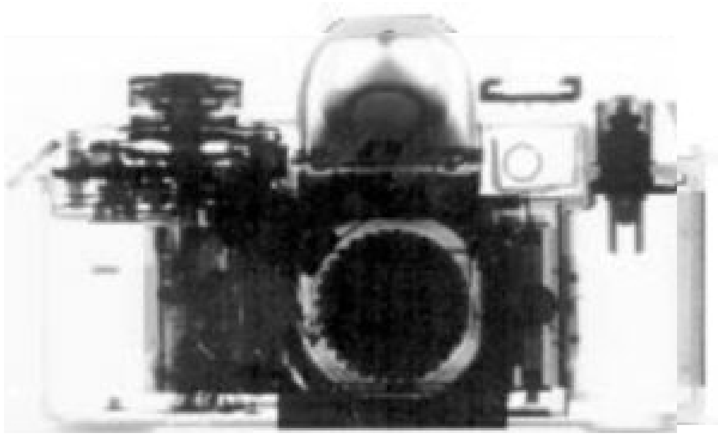
Neutron radiography

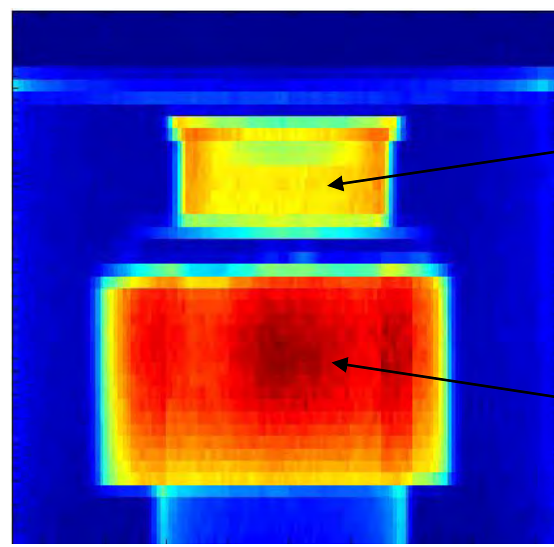
- Neutron and x-ray images complementary to one another
- X-ray attenuation increases with atomic mass
- Neutron attenuation is random with respect to atomic mass
- Resolution limited by source size for x-rays and neutrons





X-ray / Neutron

(Paul Scherrer Institut, http://neutra.web.psi.ch/What/index.html)



Plastic annulus inside Pb annulus

Pb box with two different circular inner diameters

Gamma-ray / Neutron

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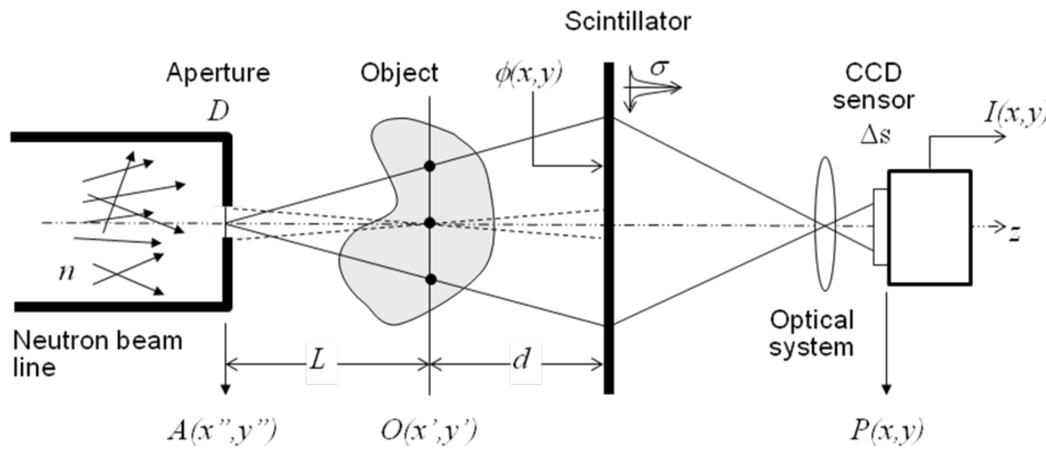
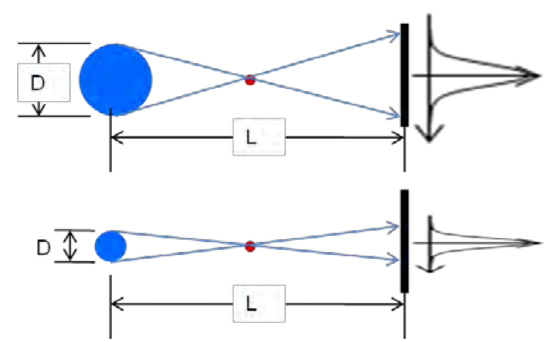
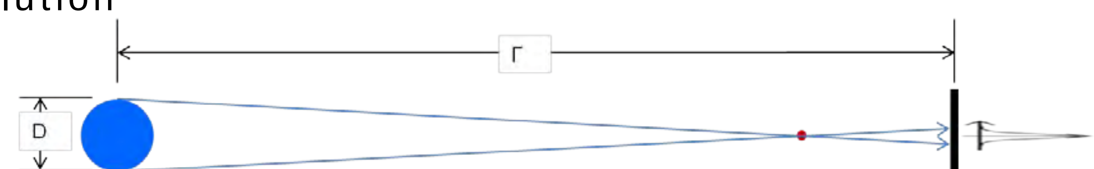
Neutron radiography
System designs

- Simple radiographic setup (source, object, detector)
  - Sources
    - Reactors, Spallation sources, Generators, and Fission sources
    - Low flux in comparison to x-ray systems
    - Large neutron facilities (10^8 n/cm^2/sec)
  - Detectors
    - Scintillator
    - Micro-Channel Plate
- Resolution driven by L, D, and object position
- Systems set high L/D and place object close to detector
- Limit in resolution by scintillator
- Magnified imaging needed for resolution
- Large source needed for SNR







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Coded aperture imaging

- Image formation

$$P(\mathbf{r}) = O(\mathbf{r}) * A(\mathbf{r})$$

- Reconstruction
  - Algorithm

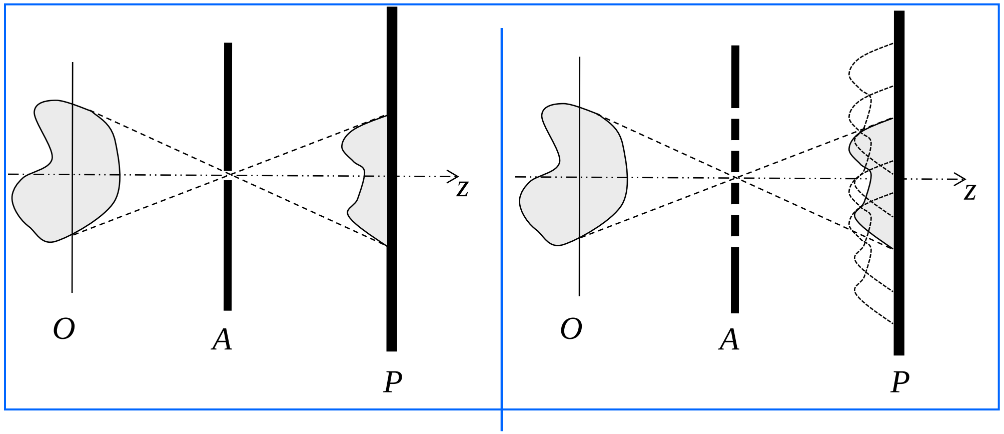
$$\hat{O}(\mathbf{r}) = P(\mathbf{r}) * G(\mathbf{r})$$

$$\hat{O}(\mathbf{r}) = O(\mathbf{r}) * \left(A(\mathbf{r}) * G(\mathbf{r})\right)$$

  - Kernel

$$\hat{O}(\mathbf{r}) = O(\mathbf{r}) \quad iff \quad A(\mathbf{r}) * G(\mathbf{r}) = \delta(\mathbf{r})$$

$$G(\mathbf{r}) \equiv \begin{cases} 1 & if \quad A(\mathbf{r}) = 1 \\ -1 & if \quad A(\mathbf{r}) = 0 \end{cases}$$



Pinhole *Coded Aperture*

Gamma system uses linear coded aperture and CsI detector "pixels"

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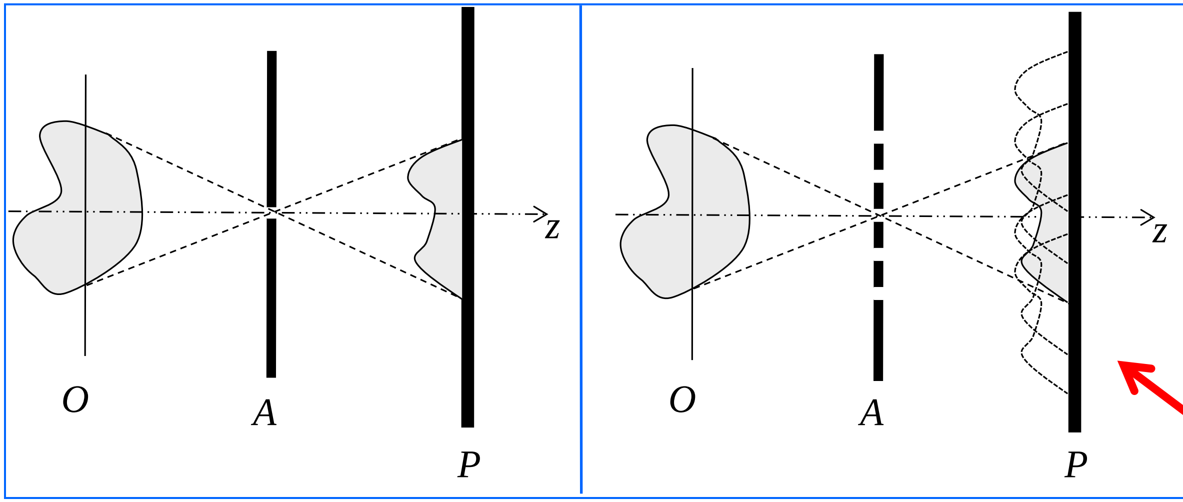
Coded source imaging

Coded Aperture Imaging

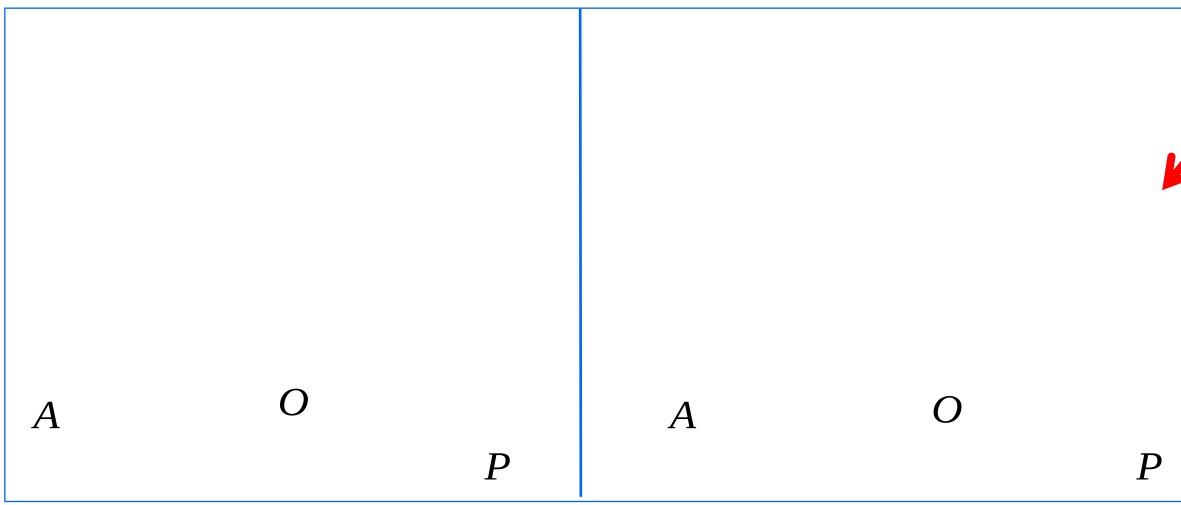


Pinhole

Coded Aperture

$$\boxed{P(\mathbf{r}) = O(\mathbf{r}) * A(\mathbf{r})}$$

Coded Source Radiography



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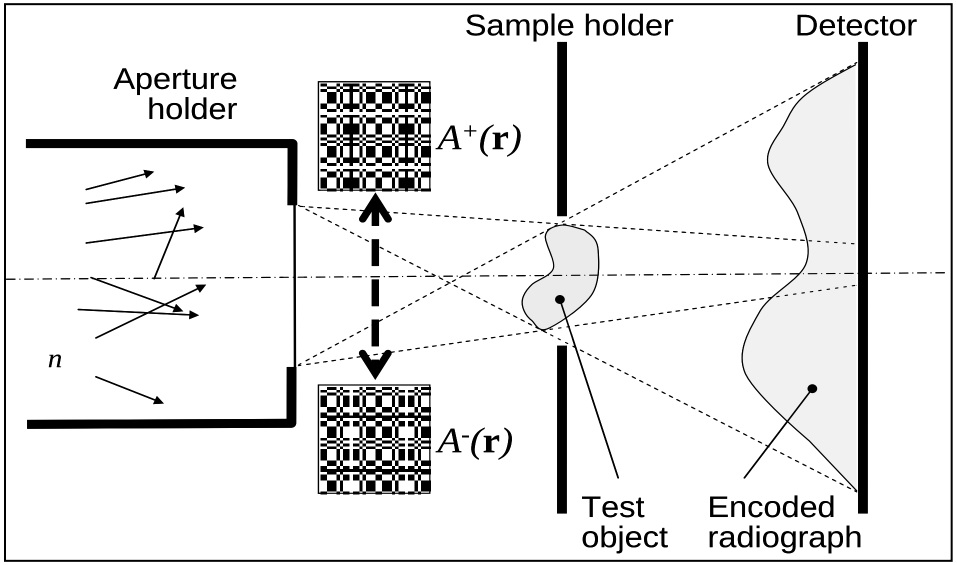
Coded source imaging system design

- Aperture and anti-aperture imaging
  - Reduce system noise
  - Near field effect reduction
- Magnification to improve resolution
  - Overcome scintillator restrictions
- Coded source enables higher flux
- Progress
  - Equations for resolution and field of view limitations developed
  - Coded aperture mask designs complete for various resolution levels
  - Initial tests for sputtering of Gd on Si wafer for high resolution mask manufacture are encouraging
  - Stage systems incorporated for mask and object positioning



$$
\begin{aligned}
O_R(\mathbf{r}) &= [P^{+}(\mathbf{r}) - P^{-}(\mathbf{r})] * G^{+}(\mathbf{r}) \\
&= \left[O(\mathbf{r}) * A^{+}(\mathbf{r}) + n(\mathbf{r}) - \left(O(\mathbf{r}) * A^{-}(\mathbf{r}) + n(\mathbf{r})\right)\right] * G^{+}(\mathbf{r}) \\
&= O_R^{+}(\mathbf{r}) + O_R^{-}(\mathbf{r})
\end{aligned}
$$

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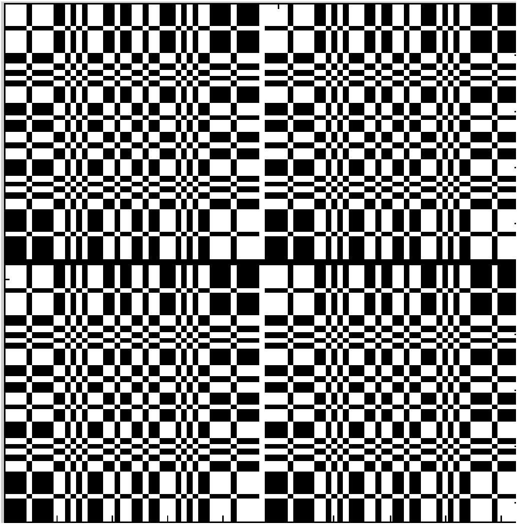
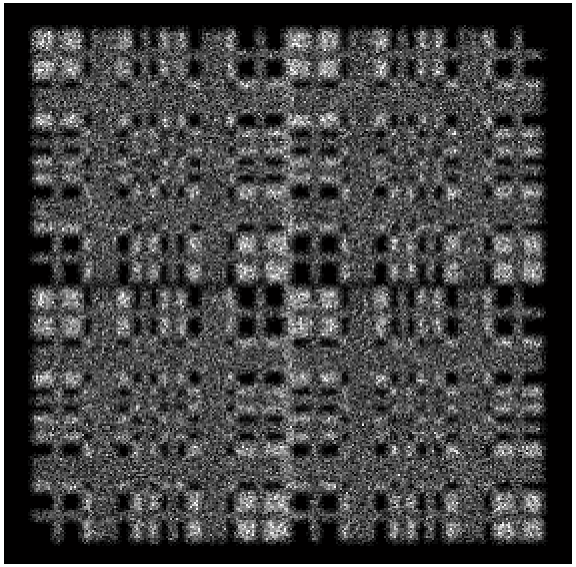
Coded source simulations

- Simulations performed with McStas
- Single pinhole object simulations
  - Image equals mask pattern
  - Allows validation of simulation model
- Pinhole array simulations
  - Test geometric limitations for FOV
  - Eventually used to study effects of percent open area on SNR
- Tilted edge simulations for MTF calculations





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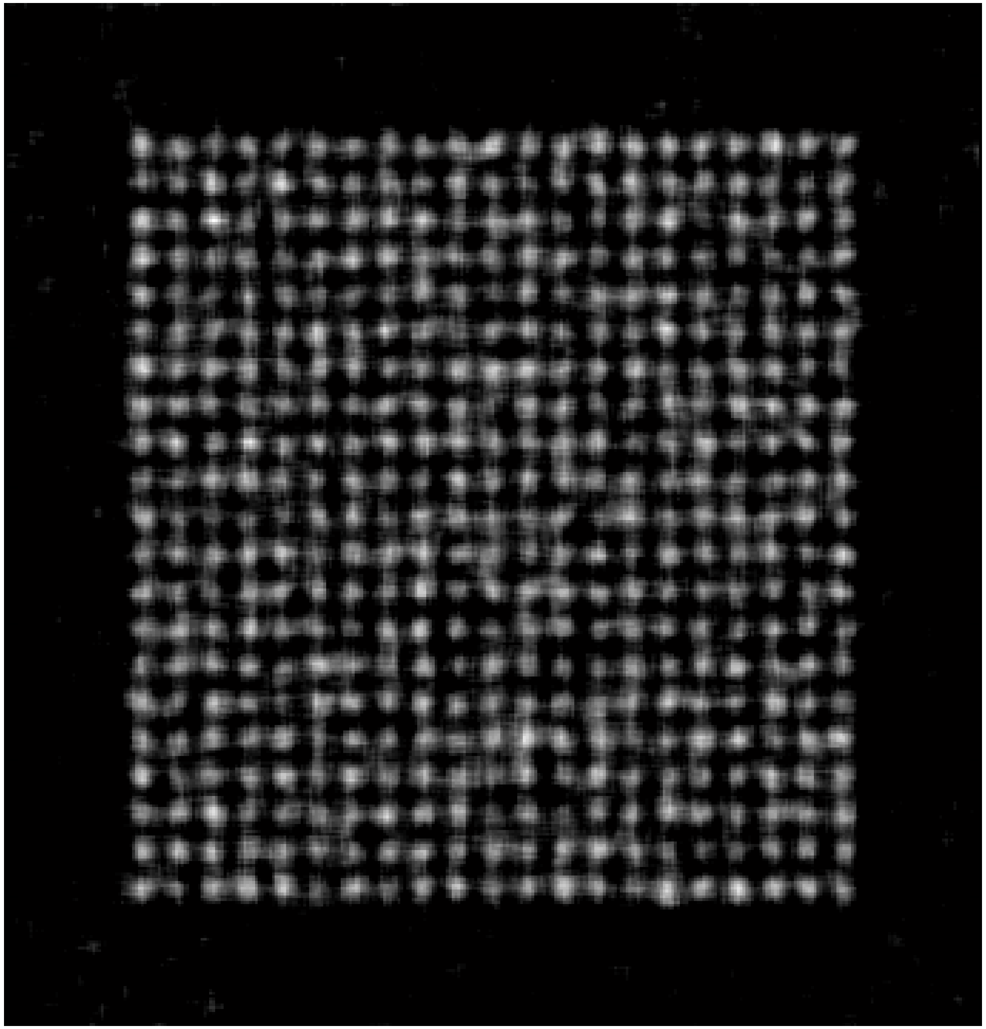
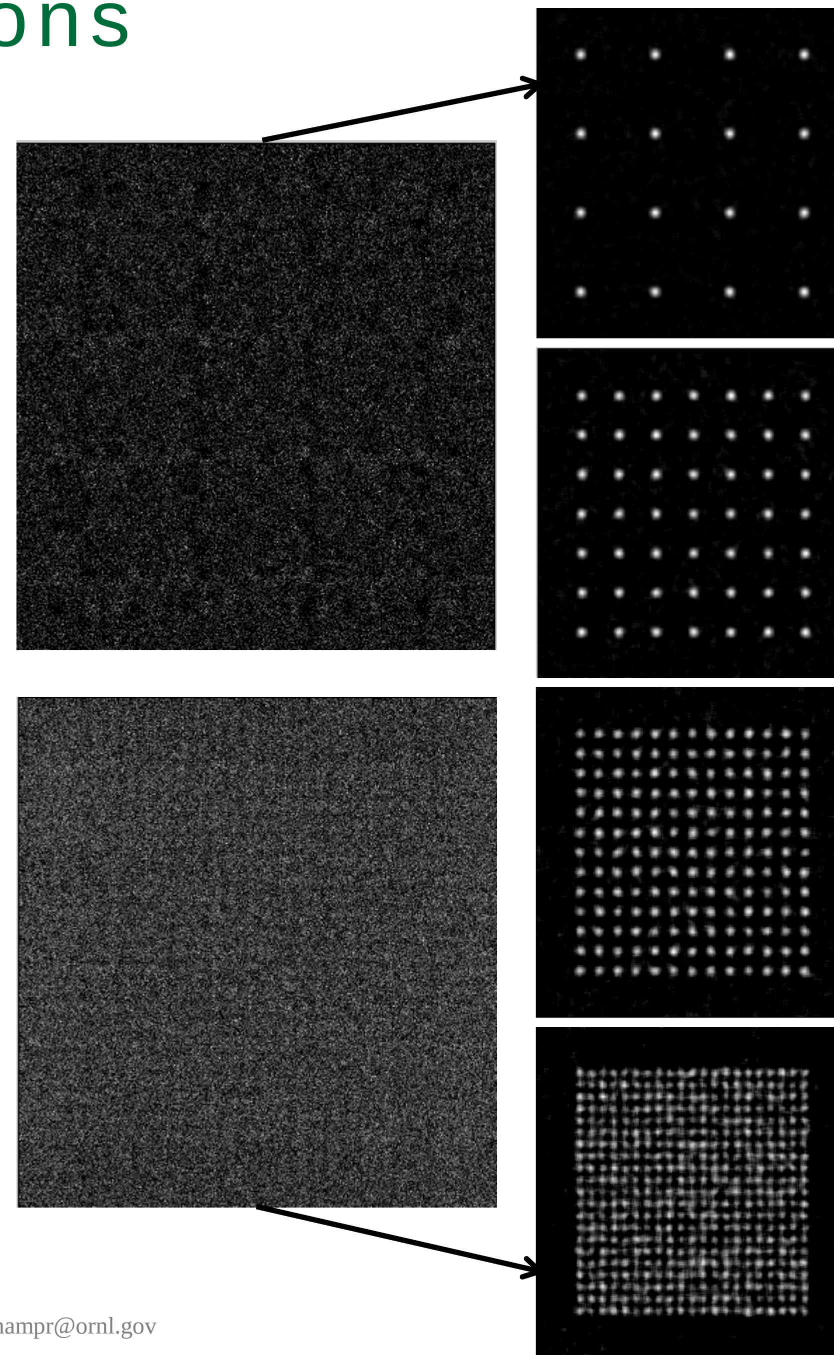
Coded source simulations
Multiple pinholes





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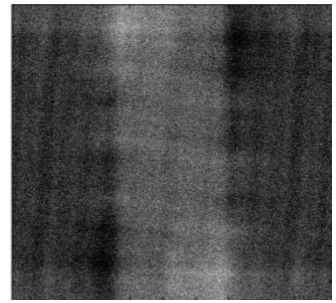
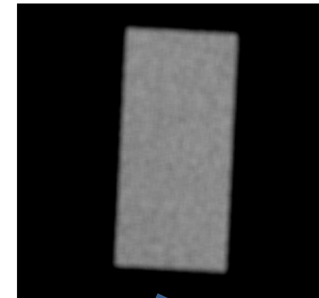
Coded source simulations
MTF Calculation from Edge Response

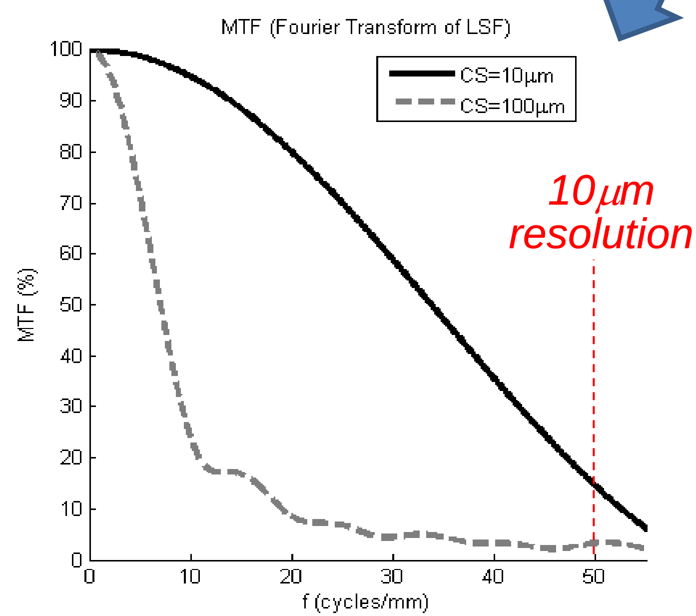
- Coded aperture
  - MURA
  - 10μm pinholes
  - 47 x 47 base pattern
- System geometry
  - CG1D setup
  - 5.2m aperture to detector
  - 577mm aperture to object
  - Object magnification of 9
  - 40μm image plane sampling

Simulated image



Reconstructed image





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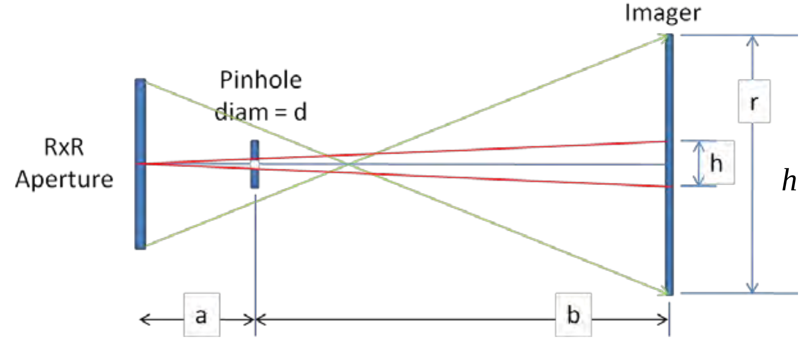
Experimentation

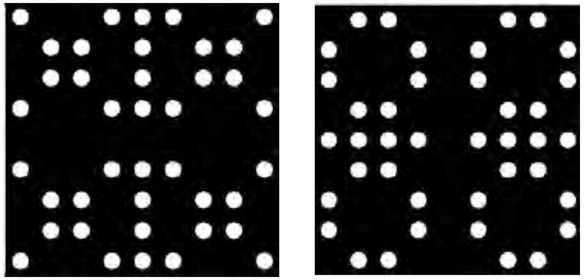
- Low resolution experiments performed
  - HFIR CG1D Neutron imaging prototype station
  - CG1A development beam line
  - Both beam lines suffer from non-uniformities in illumination
- CG1A experiment details
  - Test setup
    - a = 50cm, b = 324-50 = 274cm, d = 1mm
    - Magnification = 6.48
  - Coded aperture
    - No two holes touching drilled holes
    - 1mm thick borated Al plate
    - R = 5pixels*0.7mm = 3.5mm
    - Hole diameter = 0.381mm
  - Object
    - Borated Al plate with 1mm diameter hole
    - Extended line objects on calibration wafer
  - Detector
    - Scintillator based CCD
    - Imaged pixel size = 33.95μm



$$r = \frac{Rb}{a}$$

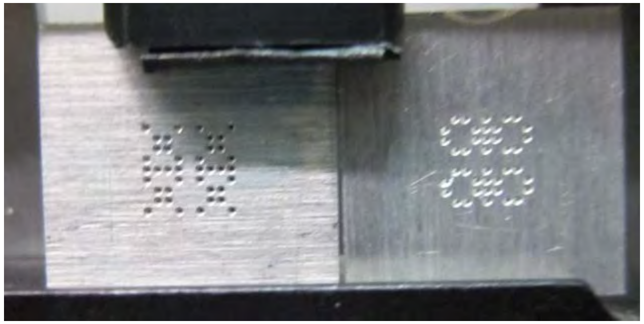
$$h = \left(\frac{a+b}{a}\right)d$$

Design



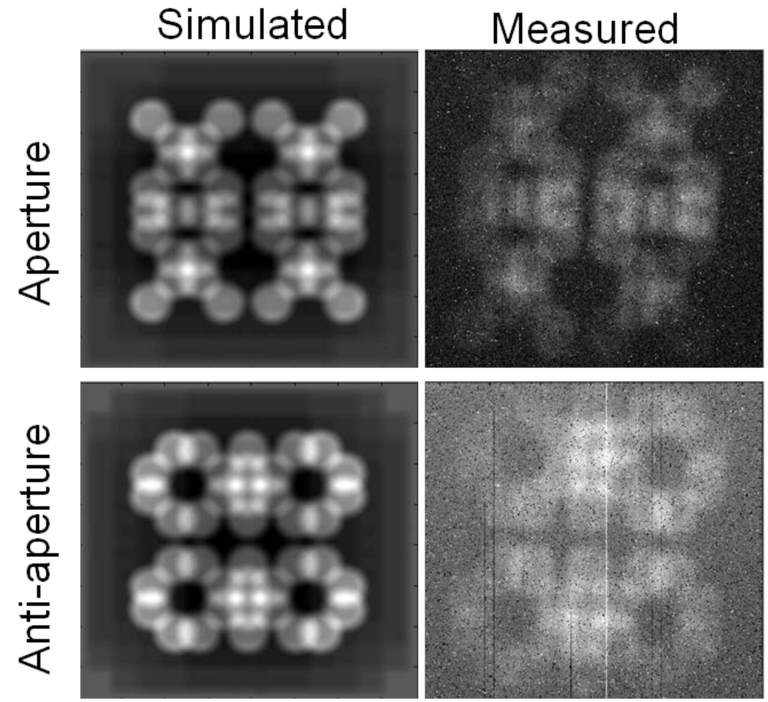
Aperture Anti-Aperture

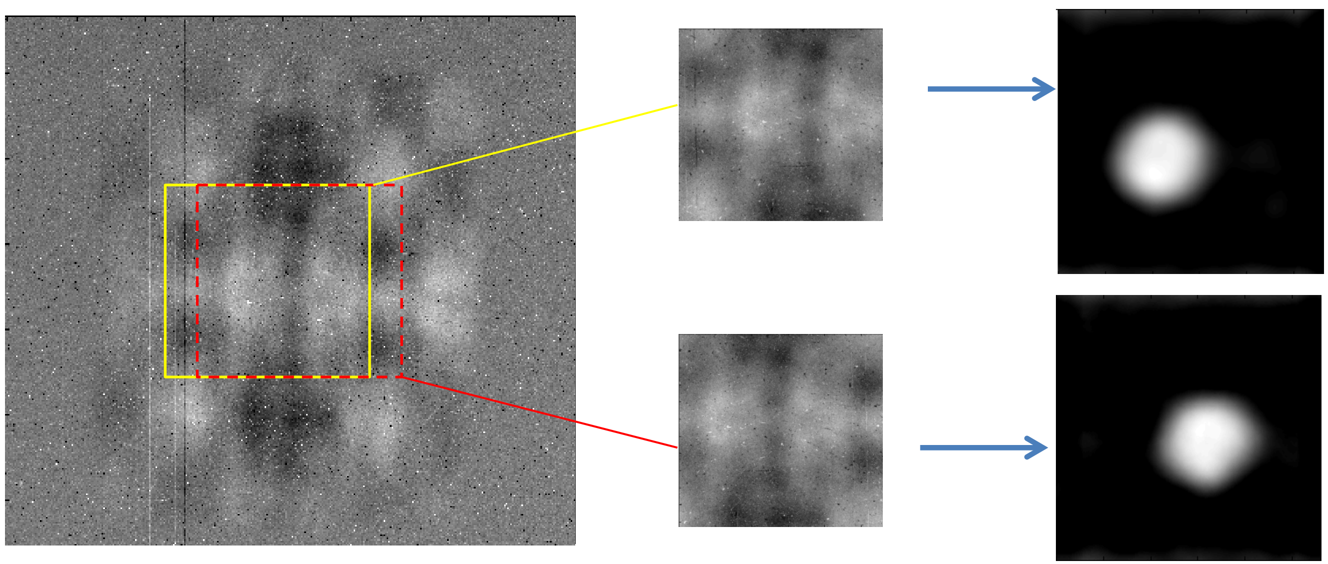
Masks



Experimentation

- 1mm pinhole image results
  - Measured image closely resembles simulation
  - Non-uniform illumination
    - Roll off of intensity in corners
    - Reconstructed pinhole shape varies with base pattern position





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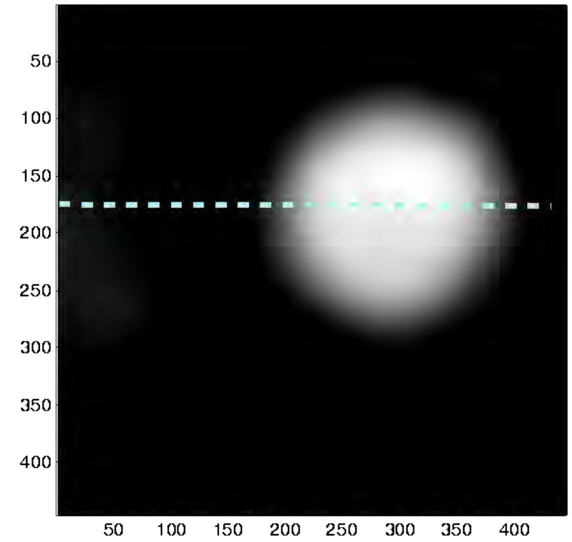
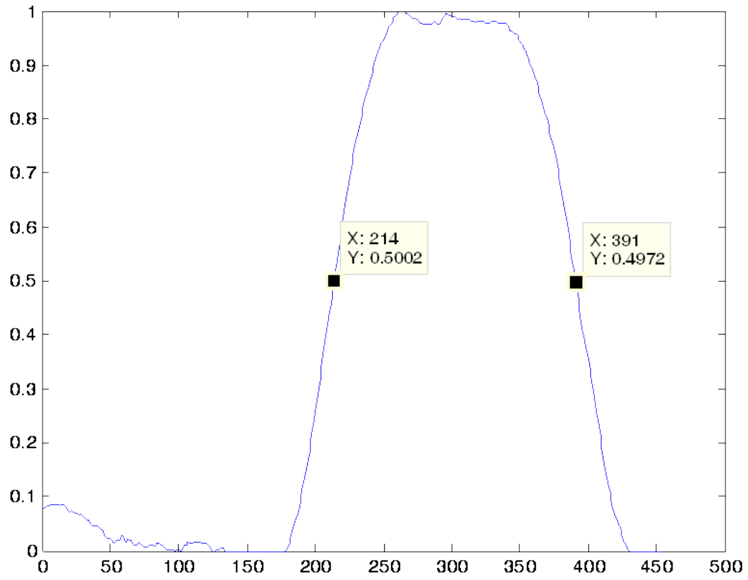
Reconstructed pinhole size matches object and magnification

- 1mm pinhole object
- Magnification of 6.48
- Imaged pixel size = 0.034mm
- Measured diameter
  - 177 pixels
  - 177*0.034/6.48 = 0.929mm
- Resolution of system
  - CA hole size = 0.381mm
  - Resolution 0.381*(324-50)/324 = 0.322mm
- Measurement well within resolution of system





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Conclusions and future efforts

- **Coded source imaging simulations have shown high resolution on extended objects**
- **Experimentation has revealed a challenge for imaging and reconstruction in the need for normalization to handle non-uniform illumination**
- **Future efforts**
  - ***Develop normalization methods for non-uniformity correction***
  - ***Extension of simulation and reconstruction algorithms to three-dimensional objects***
  - ***Addition of x-ray radiography perpendicular to neutron beam***
  - ***Develop mask manufacture method***
- **Thanks to US Department of Energy – Basic Energy Sciences for project funding through their Early Career Program and support of the CG1D user facility**

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