Hard x-ray imaging on NIF
CEA-NNSA Joint Diagnostic Meeting
Rochester, NY, June 2016

Louisa Pickworth
Overview of hard X-ray imaging

- Summary of existing imaging systems for ICF and HED plasmas
- Motivational experiments that require hard x-ray imaging
- Simple specification of the ideal system
- Issues common in hard x-ray imaging. It’s all about the collection efficiency!
- Implementations at NIF (and Z) of high throughput (large solid angle) x-ray microscopes for hard x-ray imaging
- Replicated shell Wolters and the R&D challenge of reaching 5 µm resolution
- What other microscope systems fit the bill?
To image ICF plasmas above 20 keV with suitable resolution requires large solid angles.

Detectors, sources and back lighters are weaker/less efficient at high energy, demanding better collection efficiency per res. element from the imaging system.
Motivation to pursue hard X-ray imaging on NIF

- ICF
  - Hot spot temperature (>15 keV, 5 µm)
  - Hot spot shape (>15 keV, 5 µm)
  - Close in radiograph (>16keV, monochromatic, 5 µm)
  - Shell density
    - Compton (>50keV, broad band, better served with point projection)
    - Self compton (50keV, mono chromatic?)
  - Double shell? (>20 keV self emission?)

- Material strength (>20keV, monochromatic, <10µm)
Difficulties of imaging Hard X-ray in ICF/HED

- Weak sources (comparatively)
- Short life time (< 1 ns, requiring high speed detectors)
- Low DQE detectors (~1%)
- Low resolution detectors (FWHM >50 μm)
- Bright low energy emission which needs to be filtered out
We have begun measuring spatially and time integrated hot spot temperature.

\[ T_e \text{ measurement, (N160411-001)} \]
\[ (50 \mu m \text{ pinholes @ 10 cm}) \]

Measured source:

\[ I = 2e \left( \frac{E-11}{kT_e} \right) \text{ J/sr/keV} \]

Where \( kT_e \) and \( h\nu \) in keV. \( kT_e \approx 4 \text{ keV} \)

Existing resolved imaging- not shown is at ~ 10 keV

Goal: Spatial resolved \( T_e \) measurement.
Requires 5 \( \mu \)m PSF, ~50 \( \mu \)m image, S/N >10 ~1keV bands @ 15, 20, 25 keV
The “ideal” specification for a $T_e$ measurement

An example for Hot spot $T_e$ measurement:

$$I_d = 2e^{-\left(\frac{E-11}{kT_e}\right)} \cdot d\Omega \cdot T \cdot \frac{DQE}{R}$$

$T_e$ 3-5keV source @ $h\nu=11-25$ keV

Detected photons/ (resolution element.keV)

Solid angle * Throughput should be $>10^{-7}$, we need $>~10^{-6}$ to allow shot to shot variation in shape, $T_e$ and size and time resolution
We have started investigating how to meet the requirement with new microscope systems

- To date, (with some notable exceptions) NIF has focused on variations of pinhole and slit imaging
  - We have recently built KB
- Crystal backlight imaging (CBI)
- Penumbra
- Wolters
Time line to achieve a high energy imaging system for HED /ICF

- FY16: Omega KB
- FY17: Crystal Backlit Imaging
- FY18: Pinhole/Penumbra
- FY19: Z-Wolter
- FY20: Can we find a intermediate technology to fill this gap?

- 5µm NIF-Wolter: R&D on roughness, Possible production
KB’s and Toroidal optics play a role for hotspot imaging at lower energies

- We have recently developed and implemented a Kirkpatrick-Baez imager (KBO)
  — Limited in solid angle

- We are in discussions exploring similar 2-mirror imaging systems (Toroids) that have a larger solid angle. See P. Troussel et al.,
  — ? How many could we get
  — ? How quickly can we make it happen
Penumbral imaging on DIXI could reveal detailed hotspot structure

Possible ICF setup w/ DIXI diagnostic:
- Pinhole diameter: 100μm
- Magnification: M=64
- DIXI-Point Spread Function: 270μm FWHM Gauss
- 10% of pixels affected by neutron noise (10% dead pixels)

Expected SNR>10
Resolution: ~5μm
Fresnel limit (a=10cm): 3.6 μm
Penumbral Imaging uses the edge of an aperture to encode the image

- Source radius $R$
- Imaged through aperture $D$
- Yielding Penumbra $2MR$ on detector

Physical limits:
- Fresnel Diffraction
- Effective optical density length scale $L$ of aperture (thickness $w$)

Technical limits:
- Det. Resolution $d$
- DQE
- SNR
- Aperture circularity $\Delta D(\theta)$

$$H \approx \sqrt{\frac{\lambda}{a}}$$

Magnification $M=b/a$
X-ray Penumbral Imaging can be a powerful technique to improve understanding of stagnated implosions

- Few μm resolution penumbral imaging has been successfully fielded on the NIF
- Manufacturing challenges of quality apertures have been overcome

**Challenges of Penumbral imaging:**
- Aperture characterization and build for high energy
- Energy selection
- Fielding in NIF (close in? )
Wolters and multilayers

- Wolter optics promise large solid
  - Current technology achieves ~30µm spatial resolution
  - Waiting on advancement of the technology to achieve ~5µm resolution
  - 3+ years and a R&D project to do this, so there is risk

- Multilayer coatings that operate at grazing incidence allow the possibility of pseudo monochromatic or band-like energy response (implemented in NIF KBO1 at 10.2keV)
  - Multilayer with higher reflectivity are of great interest...
Wolter for Z at Sandia

- Imaging $K_\alpha$ emission to diagnose stagnation conditions
- Wolter microscope ($M=3.5$) on the Z target chamber with optic ~70 cm from the pinch
- Geometry similar to what has been previously demonstrated with multi-layer Wolters
### Wolter for Z at Sandia

<table>
<thead>
<tr>
<th>Need</th>
<th>Goals</th>
<th>Driver</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon energies (Kα’s)</td>
<td>Mo: 17.479 keV</td>
<td>Study K-shell radiators from Ag to W</td>
</tr>
<tr>
<td></td>
<td>Ag: 22.163 keV</td>
<td></td>
</tr>
<tr>
<td></td>
<td>W: 59.318 keV</td>
<td></td>
</tr>
<tr>
<td>Spectral window</td>
<td>~1 keV</td>
<td>Simultaneously view Kα 1 &amp; 2 from cold and low-ionization states</td>
</tr>
<tr>
<td>Field of View</td>
<td>2 cm in each direction</td>
<td>Collect all emission from 2 cm pinch. Kα emission comes from large diameter</td>
</tr>
<tr>
<td>Spatial Resolution</td>
<td>~100 µm</td>
<td>Resolve length-scale of structures emitting Kα</td>
</tr>
<tr>
<td>Time resolution</td>
<td>Time integrated initially ~1 ns in 3-5 years</td>
<td>Resolve evolution over pulse</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>100 J from ~cm³ source with good S/N</td>
<td>Able to record 100 J over full source area</td>
</tr>
</tbody>
</table>

Other considerations

- Survivable (optic at >40 cm from source)
- Hard x-ray background (1-inch W in LOS)
Advancing Wolter optics to 5µm resolution for NIF

- Ability to focus is limited by low-spatial frequency errors (i.e. “figure”)
- Resolution degrades off-axis even for perfect mirrors (i.e. $\Delta \alpha = 0$):
- To first order, the angular resolution of the optic is driven by angular resolution of the master mandrel

**Main Challenge**: Achieving small figure errors on small mandrels

**Additional challenges**: Minimizing electric-field edge effects in tuning the electro-plating processes for small-radius, “stubby” optics (those, in theory, ideal for NIF)
→ Results in difficulties to achieve the same figure quality in replicated optic as in mandrel

**Current best performance** for NASA MSFC replicated optics from optics with $L = 300 \text{ mm} \times 2$ and radius of 35–60 mm (larger than what is needed for NIF)
Path to high resolution Wolter optics for NIF

Preliminary NIF design: Total throw 8.0 m, grazing angle $\geq 0.4^\circ$

<table>
<thead>
<tr>
<th>Mag $\Delta \alpha$</th>
<th>1&quot;</th>
<th>2&quot;</th>
<th>3&quot;</th>
<th>4&quot;</th>
<th>5&quot;</th>
<th>6&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>5</td>
<td>10</td>
<td>15</td>
<td>20</td>
<td>25</td>
<td>30</td>
</tr>
<tr>
<td>12</td>
<td>4</td>
<td>8</td>
<td>13</td>
<td>17</td>
<td>21</td>
<td>25</td>
</tr>
</tbody>
</table>

Current

1-2 years (comfortable with R&D)

2-3 years (challenging)
Comparison of hard X-ray microscope systems for hotspot imaging

<table>
<thead>
<tr>
<th>Approx. Solid angle/throughput</th>
<th>Multiple 5µm Pinholes mounted on target</th>
<th>Penumbra mounted on target</th>
<th>CBI</th>
<th>Wolter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1e-7</td>
<td>1e-7*filter</td>
<td>2e-6</td>
<td>1e-6<em>R²</em>efficiency</td>
<td></td>
</tr>
</tbody>
</table>

| Number of images | 10                                      | 1                           | 1   | 1      |

<table>
<thead>
<tr>
<th>Source</th>
<th>*5µm , 5mm from TCC</th>
<th>*100µm, 8cm from TCC, Mag 16</th>
<th>*60eV band,</th>
</tr>
</thead>
</table>
Summary: Hard x-ray imaging at NIF

- We are implementing several imaging systems on NIF to image (spatially and temporally resolved) hard X-rays
- Penumbral imaging and Wolter optics are the two technologies we have focused our efforts on
- Wolter optics with the desired resolution (5um) are years away (2020)
- Can we apply a different technology in the mean time?
KBFRAMED results: LANL-HED 18-Feb-2015

OMEGA shot 76276

KBFRAMED time integrated images
Filter: 5 mils Be, 4 mils Al
200 x 200 µm region

image 6

image 7

image 8

F. J. Marshall
26 Feb 2015
Crystal backlight imager

- Primarily designed for backlight application for “close in imaging” at ~16keV
- We could adapt the system for self emission
- A good amount of R&D is needed to test making and using crystals at 20 keV
- Promises large solid angle, but very narrow energy band (~60eV)