Self-emission crystal imaging and spectroscopy for MagLIF.


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The development of the Magnetized Liner Inertial Fusion (MagLIF) concept has motivated the development of new diagnostics.¹

Graphic by C.A. Jennings
We use spherically bent crystal optics to image the x-ray, self-emission from our MagLIF targets.

**Diagnostic setup**

- **Spherical crystal**
- **Rowland Circle**
- **Target**
- **Debris aperture**

**As fielded, spherically bent crystal**

- **Ge (220)**
- **1 cm**

**Magnified (6x), “monochromatic” image**
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**Diagnostic setup**

- Spherical crystal
- Rowland Circle
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**Advantages of crystal imaging:**
- Image energy range is well-defined
- High-sensitivity rel. to pinholes
- Increased detector survivability

**Disadvantages of crystal imaging:**
- Field-view limited by crystal size
- Astigmatism limits the spatial resolution
- Crystals are not cheap & are fragile

**Magnified (6x), “monochromatic” image**
Our crystal imager was designed to selectively image the Ar K-shell line at 3.12 keV. Images are time integrated.

Expected Ar emission spectra from preheated fuel

Higher energy reflections also occur at n x 3.12 keV where n=1,2,3,...

Spherical crystal imager

Detector: Fuji TR Image Plate
Located 85 cm from crystal
Our crystal imager was designed to selectively image the Ar K-shell line at 3.12 keV. Images are time integrated.

Expected Ar emission spectra from preheated fuel

Higher energy reflections also occur at n x 3.12 keV where n=1,2,3,....
The absolute sensitivity for each energy band was estimated by calculating the total instrument throughput using calculated crystal reflectivities.*

*The throughput estimates include filtering and the image plate response. Reflectivity curves are calculated using the XOP software routines (M. Sanchez del Rio, SPIE 2011)
The spatial resolution is limited by astigmatic nature of the off-axis imaging. The resolution was estimated using the SHADOW* ray tracing code.

Ray Tracing w/SHADOW

Spatial Resolution Estimates

<table>
<thead>
<tr>
<th></th>
<th>Ar emission (δE = 1.3 eV)</th>
<th>Continuum emission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical resolution</td>
<td>84 µm</td>
<td>84 µm</td>
</tr>
<tr>
<td>Horizontal resolution</td>
<td>16 µm</td>
<td>60 µm</td>
</tr>
</tbody>
</table>

- **Continuum emission**: resolution improves in both directions with a smaller crystal.
- **Line emission**: Vertical resolution will primarily improve with a smaller crystal.

*M. Sanchez del Rio, SPIE 2011
The continuum emission generated during the liner stagnation shows complex structure and non-uniformity in the vertical direction.

The average, radial width is around 100 µm, which is approaching the diagnostic limit of 60 µm.
Simple SPECT3D* simulations indicate the stagnation images are primarily a superposition of 6.2 and 9.4 keV emission.

**SPECT3D setup**

**Deuterium core**
- 100 µm dia.
- $T_e = T_i = 2.5$ keV
- 0.4 g/cc

**Be**
- 0.5 mm thick
- $T_e = T_i = 0.01$ keV
- 18.5 g/cc

*SPECT3D is a collisional-radiative spectral analysis code produced by Prism Computational Sciences, Inc.*
Simple SPECT3D* simulations indicate the stagnation images are primarily a superposition of 6.2 and 9.4 keV emission.

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Iron impurities occur in our Be targets as micron-sized particles that appear to be uniformly distributed.

The bright specks are Fe particles embedded in Be (Materion, S-65 grade). Fe impurity level is ~ 100 ppm as measured by Materion with ICPS.
To resolve the Fe emission generated at stagnation we use a spherically-bent crystal spectrometer.

Spherical crystal spectrometer\(^1\)

\(^1\)E.C.Harding et. al., RSI (2015)
D. Sinars et. al. JSQRT (2006)
FSSR used on dynamic hohlraum capsule implosions
The existing XRS\(^3\) spectrometer was optimized for the detection of the weak He-like Fe emission, while maintaining high-spectral resolution.

### Spectrometer setup for He-like Fe emission

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystal</td>
<td>Q20-23 (2d = 2.749 Å)</td>
</tr>
<tr>
<td>Source-to-crystal</td>
<td>800 mm</td>
</tr>
<tr>
<td>Crystal-to-detector</td>
<td>256.92 mm</td>
</tr>
<tr>
<td>Crystal Radius</td>
<td>250 mm</td>
</tr>
<tr>
<td>Center Bragg Angle</td>
<td>40°</td>
</tr>
<tr>
<td>Crystal size(^1)</td>
<td>60 x 36 mm</td>
</tr>
<tr>
<td><strong>Spectral Range</strong>(^2)</td>
<td>6328 - 7977 eV</td>
</tr>
<tr>
<td><strong>Spatial Mag.</strong> (M_{sag})</td>
<td>0.30x</td>
</tr>
<tr>
<td><strong>Spectral Resolution</strong>(^3)</td>
<td>2 eV</td>
</tr>
<tr>
<td><strong>Spatial Resolution</strong>(^3)</td>
<td>210 µm</td>
</tr>
<tr>
<td>Throughput</td>
<td>1.9e-7 steradians</td>
</tr>
</tbody>
</table>

\(^1\)This is a tiled crystal consisting of 2 strips, each one is 60 x 18 mm

\(^2\)Detector length must be 85 mm to capture entire spectral range.

\(^3\)Limited by the Image Plate resolution of 63 microns.
We believe we are observing He-like Fe emission from stagnation. The crystal image and spectra can be aligned using the spatial fiducials attached to the target.

Shot z2850, $Y_{DD} = 3.1e12$

Crystal Image

Space resolved, Fe spectra

Fe Kα$_{1,2}$  He-like Fe + sats.
He-like Ni + sats
Fe He-β
Ni Kα$_{1,2}$
The Fe He-like emission can be fit with synthetic spectra from PrismSPECT to estimate $T_e$ and $n_e$.

$T_e = 1.6 \text{ keV}, \quad n_e = 2 \times 10^{23} \text{ cm}^{-3}$

$T_e = 1.3 \text{ keV}, \quad n_e = 9 \times 10^{22} \text{ cm}^{-3}$

Note: Prism calculations are 1D, nLTE, steady-state, and assume 10% Be mix with .001% Fe. Optical depth of Fe w-line ~ 0.1 to 0.2 ODs.
A time-gated detector is needed to further increase the accuracy with which we can interpret the image and spectral data.

- The MagLIF platform requires only modest time resolution to have an impact on our understanding.

Target timeline

<table>
<thead>
<tr>
<th>0</th>
<th>2</th>
<th>4</th>
<th>40</th>
<th>42 ns</th>
<th>45 ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser preheat</td>
<td>Stagnation</td>
<td>Post-stagnation emission</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(a) Time gating could be used to separate x-ray emission from these events. (b) 1 ns with 8 frames could coarsely resolve each event. This will help constrain non-steady calculations.

- Ultimately, 0.25 ns resolution is required to fully resolve stagnation.
Backups
The integrated line intensity ratio of the Fe resonance (w) to intercombination (y) line show sensitivity to fuel density.

10% uncertainty in line ratio measurement yields 0.4 g/cc +/- 0.1 g/cc (25% uncertainty)
The integrated line intensity ratio of the Fe resonance (w) to satellite line j (or k) show sensitivity to fuel $T_e$.

Increasing density from 0.1 to 1 g/cc

10% uncertainty in line ratio measurement yields 2.5 keV +/- 0.3 keV (12% uncertainty) w/density uncertainty included.
The width of the Fe He-beta line shows some sensitivity to fuel density. With increases ~ 0.3 eV per 0.1 g/cc. Doppler broadening will also increase the width.