High-Resolving-Power, Ultrafast Streaked X-Ray Spectroscopy on OMEGA EP

Channel 1
- X-ray streak camera
- Chamber wall
- Crystal chamber
- Re-entrant tube with collimators

Channel 2
- X-ray CCD
- 1.65 m

Normalized signal

Pulse duration: 10 ps

500 \times 500 \times 20-\mu m \text{Cu}; 400 J
250 \times 250 \times 10-\mu m \text{Cu}; 650 J
250 \times 250 \times 2-\mu m \text{Cu}; 650 J

X-ray energy (eV)

K_{\alpha_1}
K_{\alpha_2}

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A high-resolving-power, streaked x-ray spectrometer is being developed and tested on OMEGA EP

- The goal is to achieve a resolving power of several thousand and 2-ps temporal resolution (February 2017)
- To understand system performance, a time-integrating survey spectrometer has been deployed on OMEGA EP
- Survey spectrometer measurements and offline testing show
  - focusing fidelity: \( \sim 50-\mu\text{m} \) line focus
  - resolving power: \( >2000 \)
  - throughput: \( \sim 10^{-7} \) ph/ph
  - shielding: 5 to 15 cm of lead
- These measurements provide a firm foundation for designing and implementing the time-resolved instrument

The instrument will ultimately be used to measure temperature equilibration dynamics and material response to ultrafast heating.
Collaborators


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A high-energy ultrafast laser can heat solid-density material on a time scale much faster than the material expands.

- Heating at high density produces exotic states of matter in extreme thermodynamic conditions\(^1\)
- The possible extremes in temperature enables novel material and radiative properties experiments\(^2\)
  - e.g., mean opacity of solar interior matter\(^3\)
- New diagnostic techniques are sought for testing
  - plasma-dependent atomic processes\(^4\)
  - plasma opacity\(^5\)
  - equation-of-state models\(^6\)

These studies require dense, high-temperature plasmas that are well characterized.

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Outer-shell ionization affects the energy and shape of the characteristic $K_{\alpha}$ line in a partially ionized plasma

- Hot electrons create K-shell vacancies when colliding with ions
- Ionization by thermal electrons removes electrons from the ions’ outer shells
- As the ionization progresses, the $K_{\alpha 1,2}$ lines increase their energy$^{1−5}$

Time-resolving the $K_{\alpha}$ line shift allows for the mean ionization state of the plasma to be inferred during the rapid heating phase.

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The instrument is based on two diagnostic channels, each with a spherical Bragg crystal.

### Channel 1
- **Si220 spherical crystal**
- **Source**
- **X-ray streak camera**
- 2.2 m

### Channel 2
- **Si220 spherical crystal**
- **Source**
- **X-ray charged-coupled device (CCD)**
- 2.2 m

### Parameter Requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirements</th>
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</thead>
<tbody>
<tr>
<td>X-ray source size</td>
<td>~100 μm²</td>
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<tr>
<td>Spectral range</td>
<td>7.97 to 8.11 keV</td>
</tr>
<tr>
<td>Crystal and Bragg angle</td>
<td>Si220 crystal—Bragg angle = 22.8°</td>
</tr>
<tr>
<td>Crystal radius of curvature</td>
<td>330 mm</td>
</tr>
<tr>
<td>Crystal size</td>
<td>25 mm × 100 mm</td>
</tr>
<tr>
<td>Source-to-crystal distance</td>
<td>2.2 m</td>
</tr>
<tr>
<td>Resolving power</td>
<td>~5000—streak-camera limited</td>
</tr>
<tr>
<td>Spectral shifts</td>
<td>Few eV to 20-eV Kα line shifts</td>
</tr>
<tr>
<td>Streak-camera slit</td>
<td>6-mm-long, 400-μm-wide</td>
</tr>
<tr>
<td></td>
<td>50-μm-high-throughput region</td>
</tr>
<tr>
<td>Temporal resolution</td>
<td>2 ps</td>
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</table>
High-power experiments show the focusing fidelity, resolving power, and throughput meet the desired requirements.

- The measured throughput is $1.4 \times 10^{-7}$ ph/ph
- The predicted peak signal at the streak camera is $\sim 1000$ ADU per pixel
- Photometric estimates are based on
  - laser energy: 100 J
  - x-ray flash duration: 10 ps
- Shifted spectra are well-matched to the length of the streak-camera slit

Phase I has provided the foundation for designing and implementing the time-resolved instrument.
Time-integrated measurements on OMEGA EP show spectral shifts increasing with target energy density.

**Spectrometer Measurements**

Pulse duration: 1 ps

Pulse duration: 10 ps

X-ray energy (eV):

- 8000
- 8050
- 8100
- 8150

Normalized signal:

- 0.0
- 0.2
- 0.4
- 0.6
- 0.8
- 1.0

Sample configurations:

- 500 × 500 × 20-μm Cu; 100 J
- 250 × 250 × 10-μm Cu; 400 J
- 250 × 250 × 2-μm Cu; 500 J
- 500 × 500 × 20-μm Cu; 400 J
- 250 × 250 × 10-μm Cu; 650 J
- 250 × 250 × 2-μm Cu; 650 J
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**Summary/Conclusions**

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- To understand system performance, a time-integrating survey spectrometer has been deployed on OMEGA EP
- Survey spectrometer measurements and offline testing show
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Model Predictions

Temporal spectral shifts on the Cu K\(_{\alpha}\) line in rapidly heated solid matter will validate the spectrometer performance

- Synthetic spectra from hot, dense matter are required
- \textit{LSP}\(^1\) calculates
  - energy-transport physics
  - electromagnetic-field generation
  - target heating
- \textit{LSP} is post-processed based on tabulated \textit{PrismSPECT}\(^2\) calculations using
  - the local density and temperature at the time of emission
  - line-of-sight and high-\(T_e\) opacity effects
- The calculations use an occupation probability model\(^3\) and the ionization potential depression formalism of More\(^4\)

\(^2\)Prism Computational Sciences Inc., Madison, WI 53711.