Streaked X-Ray Imaging of Ultrafast Ionization Waves Inside a Metal

P. M. Nilson
University of Rochester
Laboratory for Laser Energetics
Hot-electron–driven ionization waves were observed inside a high-intensity laser-irradiated metal target.

Summary

- A new, monochromatic, streaked x-ray crystal imager has been developed for the OMEGA EP laser to study collisional ionization wave dynamics.
- Spatial, spectral, and temporal resolution are obtained by coupling a spherically bent crystal imager with a 2-ps-resolution x-ray streak camera.
- The flow of hot-electron–induced $K_\alpha$ emission has been tracked through a metal target.

Ionization-wave speed: $(0.11 \pm 0.02)c$
Collaborators

G. Fiksel¹, C. Stoeckl¹, P. A. Jannimagi¹, C. Mileham¹, W. Theobald¹, J. R. Davies¹,², J. F. Myatt¹, A. A. Solodov¹,², D. H. Froula¹, R. Betti¹,²,³, and D. D. Meyerhofer¹,²,³

¹Laboratory for Laser Energetics
University of Rochester, Rochester, NY

²Fusion Science Center for Extreme States of Matter
University of Rochester, Rochester, NY

³Departments of Mechanical Engineering and Physics
University of Rochester, Rochester, NY
WDM creation relies on generating intense flows of energy inside solid- and laser-compressed matter.
Hot-electron refluxing in mass-limited targets accesses high-temperature matter at solid density

- Refluxing is caused by Debye-sheath field effects*
- Majority of hot electrons are stopped in the target
- Efficient $K_\alpha$ radiators

Debye sheaths $|E| \approx 10^{12} \text{ V/m}$

Fastest electrons escape

$K_\alpha$ production

$10^{19}$ W/cm$^2$

500 $\mu$m

20 $\mu$m

---

Spatial, spectral, and temporal resolution are obtained by coupling a spherical crystal imager with an ultrafast x-ray streak camera.

---

Streaked $K_\alpha$ imaging shows a collisional ionization wave and ultrafast energy transport into the target.

Laser: 250 J, 10 ps
Target: 500 $\times$ 500 $\times$ 20-$\mu$m$^3$ Cu

- The FWHM of the impulse-response function is subtracted from the streak-camera trace in quadrature

$K_\alpha$ flash time (FWHM): (12.0$\pm$0.1) ps
The ionization wave is observed to move with a speed of $0.11 \pm 0.02 \, c$

- Data from several adjacent time steps are grouped together into a single bin to estimate statistical errors.
- The error bars report the standard deviation for each bin.
- Suggests the ionization-wave speed increases with time.
The ionization wave is driven by a time-dependent hot-electron source with an intensity-dependent hot-electron temperature

- LSP* calculates hot-electron flow
  - 250-J, 10-ps pulse
- Hot-electron source is prescribed with varying energy
- Full target volume and interaction time scale are modeled
- LSP calculates electromagnetic fields self-consistently—accounts for refluxing

\[
\log_{10} n_e \text{ (cm}^{-3}\text{)}
\]

<table>
<thead>
<tr>
<th>Time (ps)</th>
<th>Distance ((\mu m))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>20</td>
<td>150</td>
</tr>
<tr>
<td>30</td>
<td>250</td>
</tr>
</tbody>
</table>


**Prism Computational Sciences, Inc., Madison, WI 53711
Summary/Conclusions

Hot-electron–driven ionization waves were observed inside a high-intensity laser-irradiated metal target

• A new, monochromatic, streaked x-ray crystal imager has been developed for the OMEGA EP laser to study collisional ionization wave dynamics

• Spatial, spectral, and temporal resolution are obtained by coupling a spherically bent crystal imager with a 2-ps-resolution x-ray streak camera

• The flow of hot-electron–induced K$_\alpha$ emission has been tracked through a metal target

Ionization-wave speed: (0.11±0.02)c
The crystal was initially aligned with a single-mode fiber laser*

- X-ray imaging on low-power shots optimized alignment

![Graphs showing target-edge lineout and system MTF with optimized and fiber-laser alignment.]

Approximately 10-\(\mu\)m resolution was measured based on x-ray imaging optimization.

A 2-ps-resolution x-ray streak camera was coupled to the crystal imager.

- Temporal dispersion in the streak camera gives a slightly different impulse response for x rays.
- Monte Carlo modeling of the electron optics inside the streak tube shows this offset is around 0.2 ps.
- The impulse response for x rays is approximately 2 ps.

\[
\begin{align*}
\text{Pulse 1: } & 1.8 \pm 0.1 \text{ ps} \\
\text{Pulse 2: } & 1.9 \pm 0.1 \text{ ps}
\end{align*}
\]