An Investigation of the Aluminum K-Edge by Spatially Resolved X-Ray Absorption Spectroscopy

Adam Cahill

Laboratory of Plasma Studies
Cornell University

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Outline

Background

Absorption Experiment

0D Model

Absorption Analysis

Results
XP stores energy in a Marx bank.
- 15 kJ in 10 capacitors
- charged in parallel
- discharged in series

Pulse compressions occur in three stages.
- XP delivers 500 kA in 50 ns or 100 ns.
The Hybrid X-Pinch

- The hybrid X-pinch uses two solid electrode cones to deliver current to the neck.
- A single wire runs through the cones.
- This provides two advantages.
  - simple assembly
  - electrode plasma eventually bridges the gap
A Point Projection Experiment

- A point projection scheme is used to study the absorption of the aluminum K-edge.
  - K-edge energy = 1559 eV
  - quartz 1010 crystal at 21°
  - spectrum recorded on BioMax-MS film
- The plasma sample is an aluminum wire.
  - 25 µm diameter
  - Al 1199 alloy ⇒ 99.99% purity
  - 120 kA current pulse measured by Rogowski coil
- The source spectrum is generated by a molybdenum hybrid pinch.
  - timing measured by PCD
Early Time Development

- The derivative of the current rises sharply $\approx 30\text{ ns}$ into the current pulse.
  - current switch into a low resistivity corona
- What happens in the wire’s core before current leaves?
  - cannot probe spectroscopically
  - use a computational approach
- An assumption of uniform current density and pressure profile allow a 0D model to be used.
  - wire diameter $<\text{ skin depth }\Rightarrow$ uniform current
  - pressure wave transit time $<\text{ computational time }\Rightarrow$ uniform pressure
Input Data

- The aluminum wire current is measured by a Rogowski coil.
- Molecular dynamics computations are provided by M. Desjarlais et al. from Sandia.
  - provides electrical conductivity as a function of density and temperature
- SESAME table 3720 from LANL is used for aluminum’s equation of state.
  - provides pressure and energy as functions of density and temperature
Shot #7446 Results

- Current (kA)
- Temperature (eV)
- Density (g/cm³)
- Resistivity (μΩ·m)
- Energy (J)
- Pressure (Mbar)
- \( \bar{Z} \)
▸ Current starts to flow at -30 ns and switches into the wire’s corona at 0 ns.
▸ Aluminum’s melting point is reached at -8 ns.
  ▸ density and resistivity change abruptly
▸ The energy required to atomize the wire (200 mJ) is reached around -4.5 ns.
  ▸ density and resistivity become nearly constant
▸ Current also stops increasing at -4.5 ns.
  ▸ changing current path, but no voltage measurement
▸ The last 4.5 ns allow for ionization and coronal formation.
What is happening to the wire throughout the current pulse?

One time resolved absorption spectrum is acquired per experimental trial.
  - time sequence assembled from multiple shots

The alignment allows the wire core and radii up to 200 µm to be captured.

The X-ray bandwidth of interest extends from 1540 eV to 1580 eV.
Example Data

Cold K-edge $\rightarrow$ Al Reference

1540eV $\rightarrow$ Energy $\rightarrow$ 1580eV

r

200μm

0μm
Absorption spectra record a plasma’s X-ray transmission.
  - Abel inversion $\Rightarrow$ density $\times$ opacity

SCRAM computes theoretical opacities that are used to construct synthetic data.

This is then compared to experimental data.

The opacity table is anchored with opacity data for room temperature solid aluminum.
Hybrid Opacity Model

- A known shortcoming of the SCRAM code is its performance near the K-edge.
  - position and shape are computed incorrectly
- An analytical function based on the Fermi distribution is blended with the SCRAM table.
  - analytical function $\Rightarrow$ K-edge (low temperature)
  - SCRAM opacities $\Rightarrow$ line absorption (high temperature)

\[
\kappa = \kappa_l + \kappa_k(1 - f)
\]
\[
f = \frac{1}{e^{(E-E_f)/kT} + 1}
\]
Matching the Data

- We seek to match the Abel inverted experimental data with theoretical results \( \rho \kappa(\rho, T) \).
  - minimize \( \chi^2 \)
- The opacity table is not suited for use with a linear solver.
  - rapid and large opacity changes at absorption lines
- The parameter space is too large for a brute force approach.
- A genetic algorithm (GA) is well suited to handle the opacity table and the large parameter space.
  - cannot guarantee convergence
Example Data

Cold K-edge → Al Reference

200μm
0μm

1540eV  Energy  1580eV

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Results

Absorption Experiment 0D Model Absorption Analysis Results

![Absorption (cm⁻¹) vs Energy (eV)]

Graph showing absorption in cm⁻¹ as a function of energy (eV) for different radii (μm): 150μm, 75μm, and 0μm.

Legend:
- Red line: 150μm
- Pink line: 75μm
- Green line: 0μm

Energy range: 1540 to 1580 eV

Absorption range: 0 to 10 cm⁻¹

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Theory vs. Experiment

Similarities

▷ Absorption lines at 1563 eV and 1572 eV agree.
▷ The mean opacities above and below the K-edge are correct.
▷ The K-edge position and slope are captured by the Fermi model.

Discrepancies

▷ An experimental line at 1566 eV is not reproduced in the opacity table.
▷ The opacity table contains a line at 1570 eV that is not observed.
▷ There are oscillations above the K-edge.
K-Edge Oscillations (Epstein et al. 1983)

- The distance between atoms in crystalline aluminum (2.9 Å) is found from the FFT of oscillations above the K-edge (top).
- Residual structure is observed 30 ns after melt (bottom).
K-Edge Oscillations in XP Data

- The observed period in the XP data is shorter than that found in solid data.
- Transforms of the experimental data reveal a peak near 3 nm.
  - not observed to change with time
  - average spacing in aluminum clusters
- Droplets have been recorded in the wire cores of other materials.
- Images of Al wire cores appeared uniform.
  - interpreted to have completely vaporized
Shock Compressed K-edge (Hall et al. 1998)

- Laser irradiation shock compressed a CH/Al/CH target.
- The energy of the K-edge is observed to decrease with compression.

![Graph showing shift and width versus compression.]
The K-edge is clearly visible at densities above $1 \times 10^{19} \text{ cm}^{-3}$.

The energy of the K-edge is found to decrease with increasing density.

The XP data’s low density makes it unique in the literature.
Conclusions

- Large range oscillations above the K-edge are reminiscent of QMD results.
  - interpreted as persistent structure from the solid state
  - smaller oscillations than QMD data $\Rightarrow$ larger ion-ion spacing
  - not found in SCRAM predictions
- Aluminum clusters create a heterogeneous environment.
  - uniformity assumptions of 0D model invalidated
  - would require significant effort to predict opacity
  - explains why SCRAM missed this
- Shifts in the K-edge are consistent with laser observations.
  - new data below solid density
  - due to rising continuum levels as density decreases