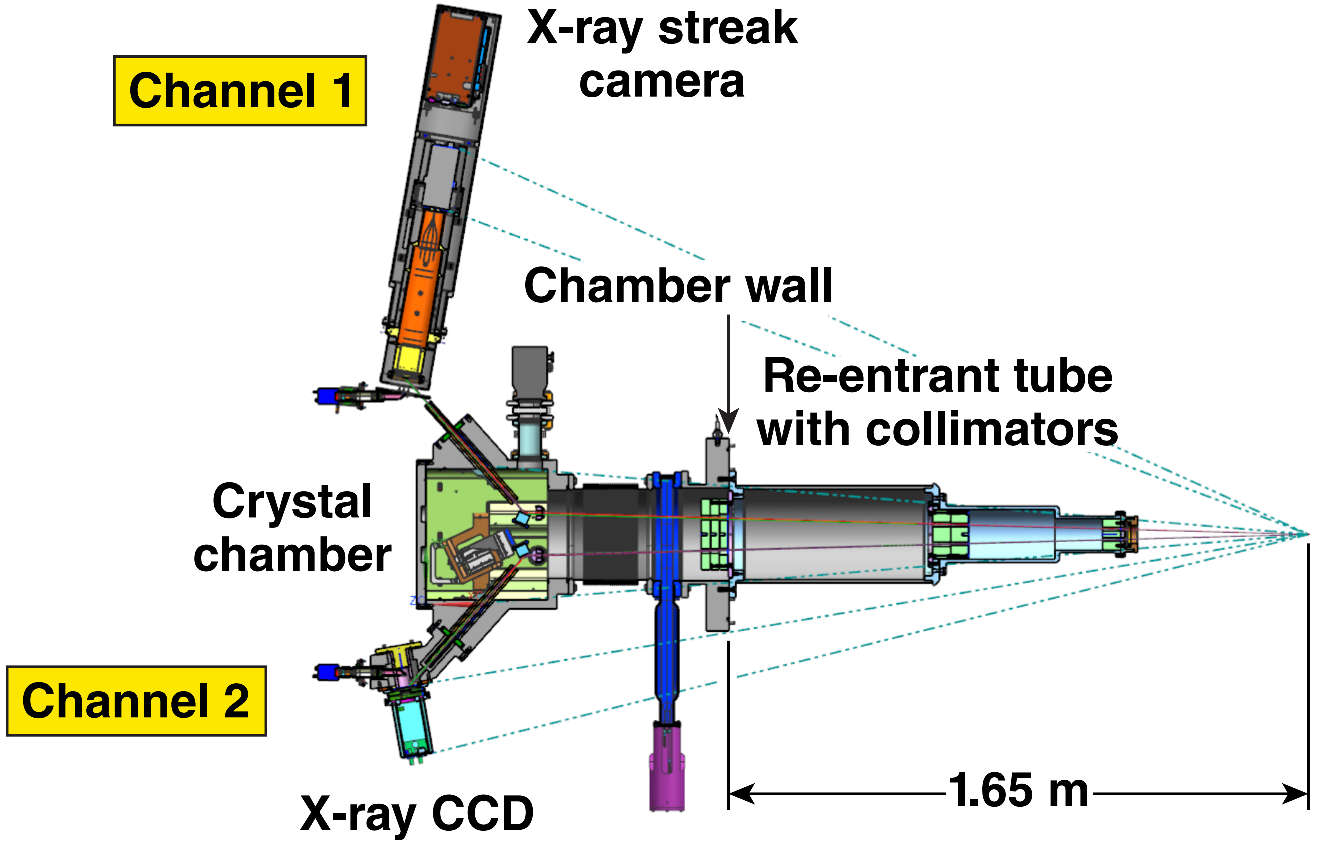
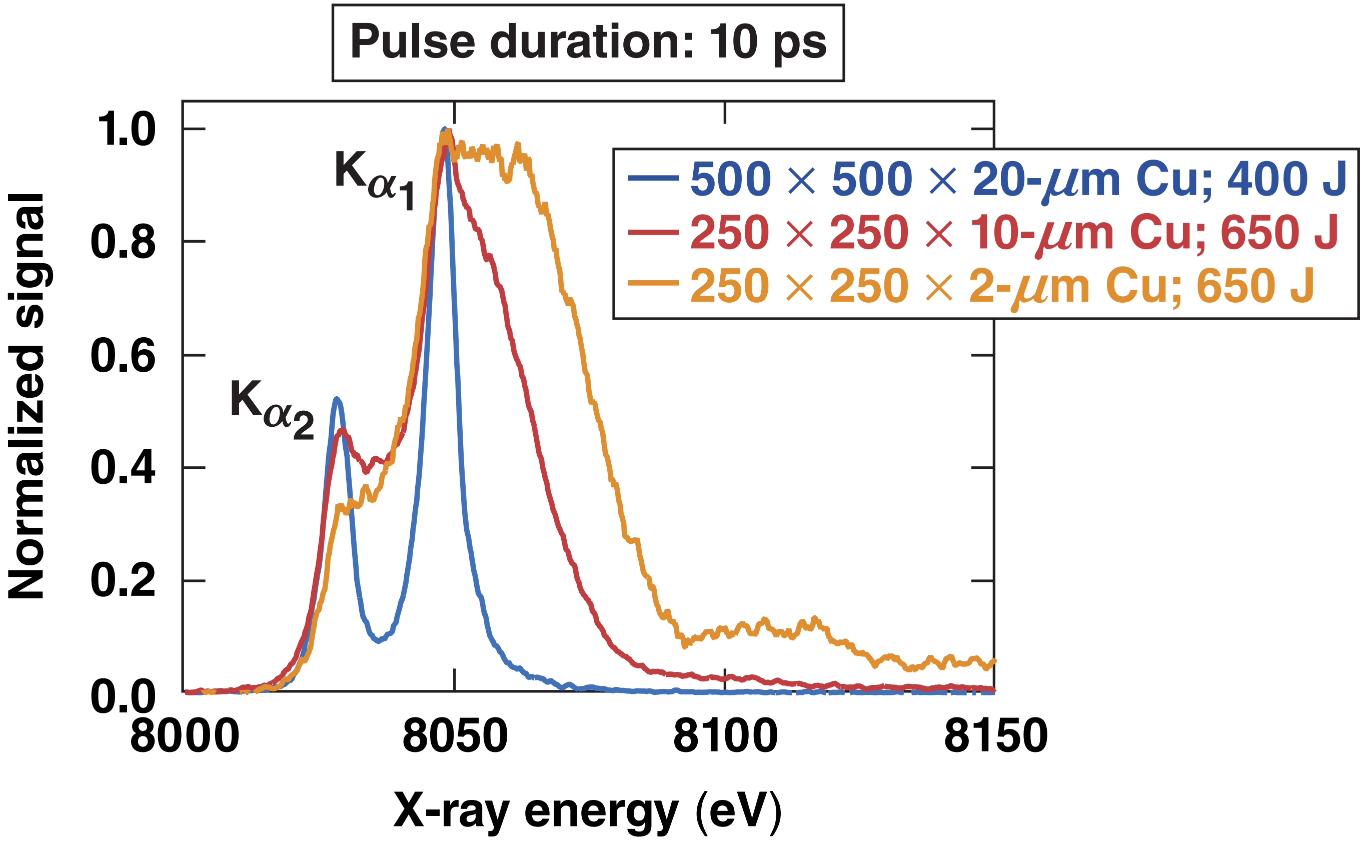
High-Resolving-Power, Ultrafast Streaked X-Ray Spectroscopy on OMEGA EP





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58th Annual Meeting of the
American Physical Society
Division of Plasma Physics
San Jose, CA
31 October–4 November 2016

Summary

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: ~50-μm line focus
  - resolving power: >2000
  - throughput: ~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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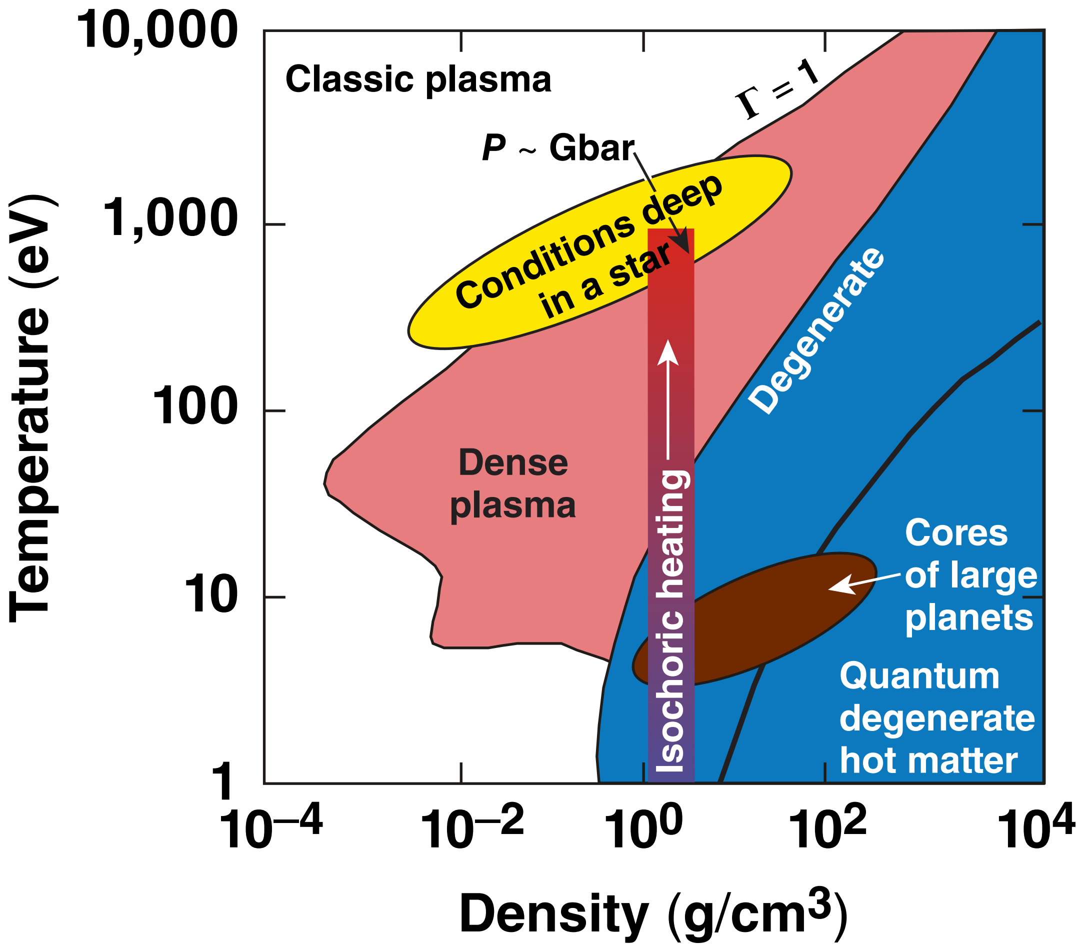
Motivation

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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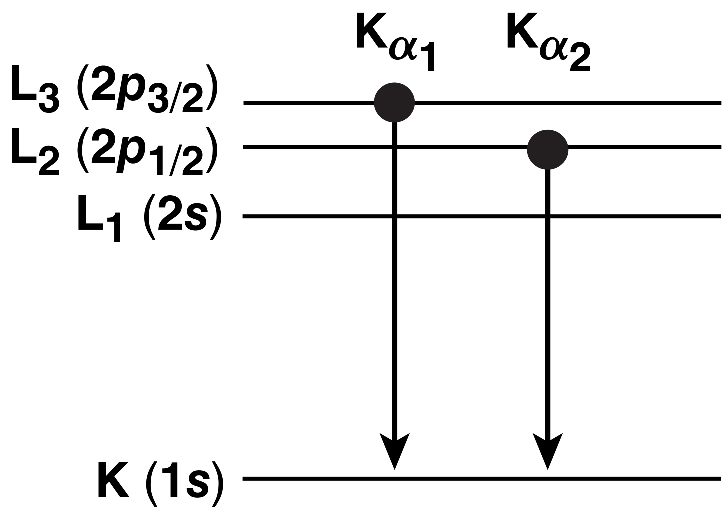
[1] A Report on the SAUUL Workshop, Washington, DC (17–19 June 2002).
[2] K. Nazir *et al*., Appl. Phys. Lett. 69, 3686 (1996).
[3] J. E. Bailey *et al*., Nature 517, 56 (2015).
[4] D. J. Hoarty *et al*., Phys. Rev. Lett. 110, 265003 (2013).
[5] R. A. London and J. I. Castor, High Energy Density Phys. 9, 725 (2013).
[6] M. E. Foord, D. B. Reisman, and P. T. Springer, Rev. Sci. Instrum. 75, 2586 (2004).

Motivation

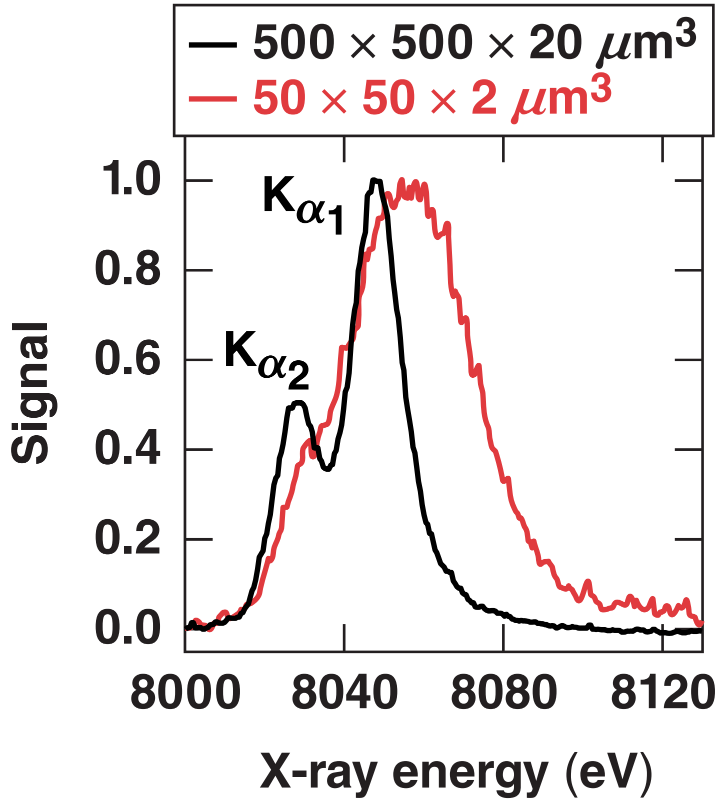
Outer-shell ionization affects the energy and shape of the characteristic K_α line in a partially ionized plasma

- 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]

Fine structure of the characteristic K_α line



MTW laser: 5 × 10^{18} W/cm^2
Target: Cu foil



Time-resolving the K_α line shift allows for the mean ionization state of the plasma to be inferred during the rapid heating phase.

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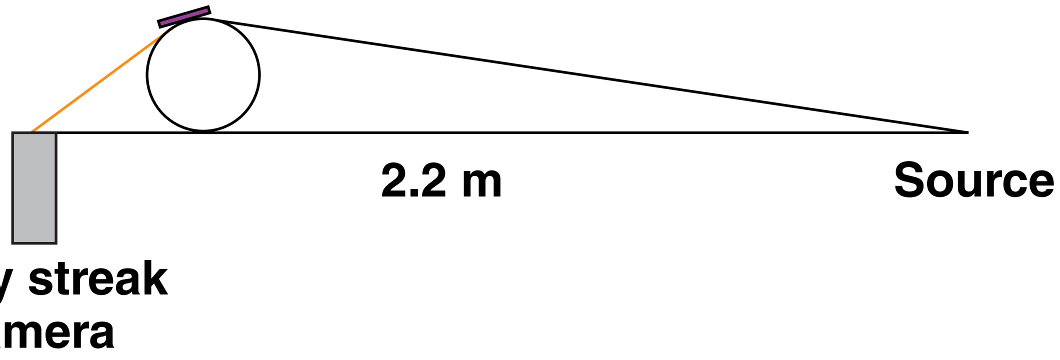
[1] K. Słabkowska *et al.*, High Energy Density Phys. 15, 8 (2015).
[2] K. Słabkowska *et al.*, High Energy Density Phys. 14, 30 (2015).
[3] G. Gregori *et al.*, Contrib. Plasma Physics 45, 284 (2005).
[4] P. M. Nilson *et al.*, Phys. Plasmas 18, 042702 (2011).
[5] J. F. Seely *et al.*, High Energy Density Phys. 9, 354 (2013).

Conceptual Design

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

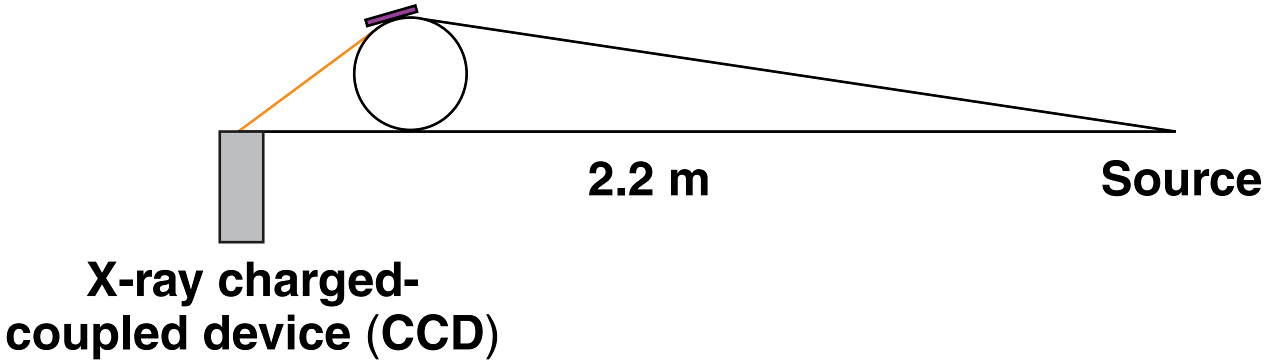
Channel 1

Si220 spherical crystal



Channel 2

Si220 spherical crystal

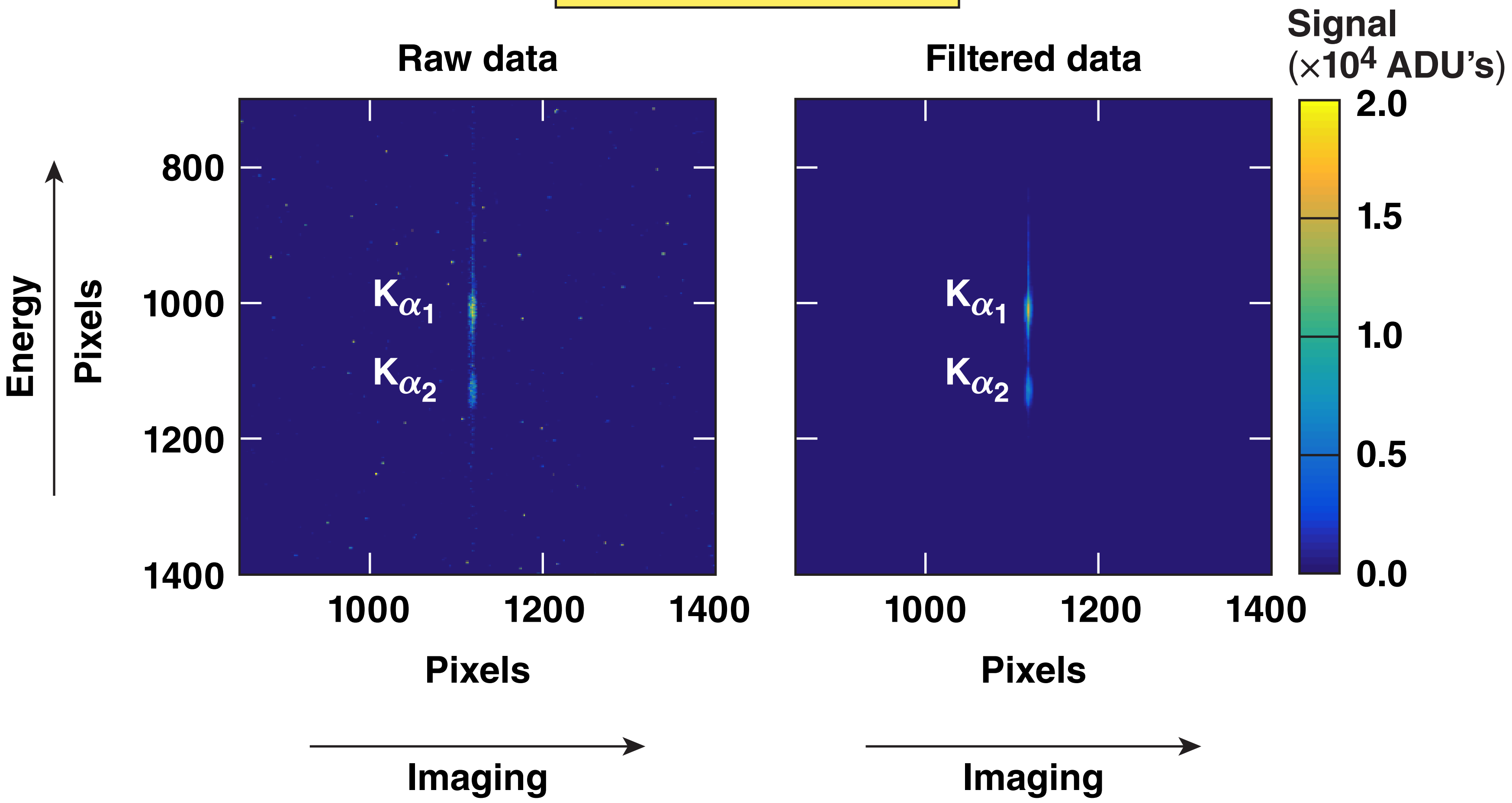


Parameter	Requirements
X-ray source size	~100 μm^2
Spectral range	7.97 to 8.11 keV
Crystal and Bragg angle	Si220 crystal—Bragg angle = 22.8°
Crystal radius of curvature	330 mm
Crystal size	25 mm × 100 mm
Source-to-crystal distance	2.2 m
Resolving power	~5000—streak-camera limited
Spectral shifts	Few eV to 20-eV K_α line shifts
Streak-camera slit	6-mm-long, 400-μm-wide 50-μm-high-throughput region
Temporal resolution	2 ps

Spectrometer Measurements

High-power experiments show the focusing fidelity, resolving power, and throughput meet the desired requirements

Shot 22854
100 J, 1 ps—Si220



- The measured throughput is 1.4×10^{-7} ph/ph
- The predicted peak signal at the streak camera is ~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.

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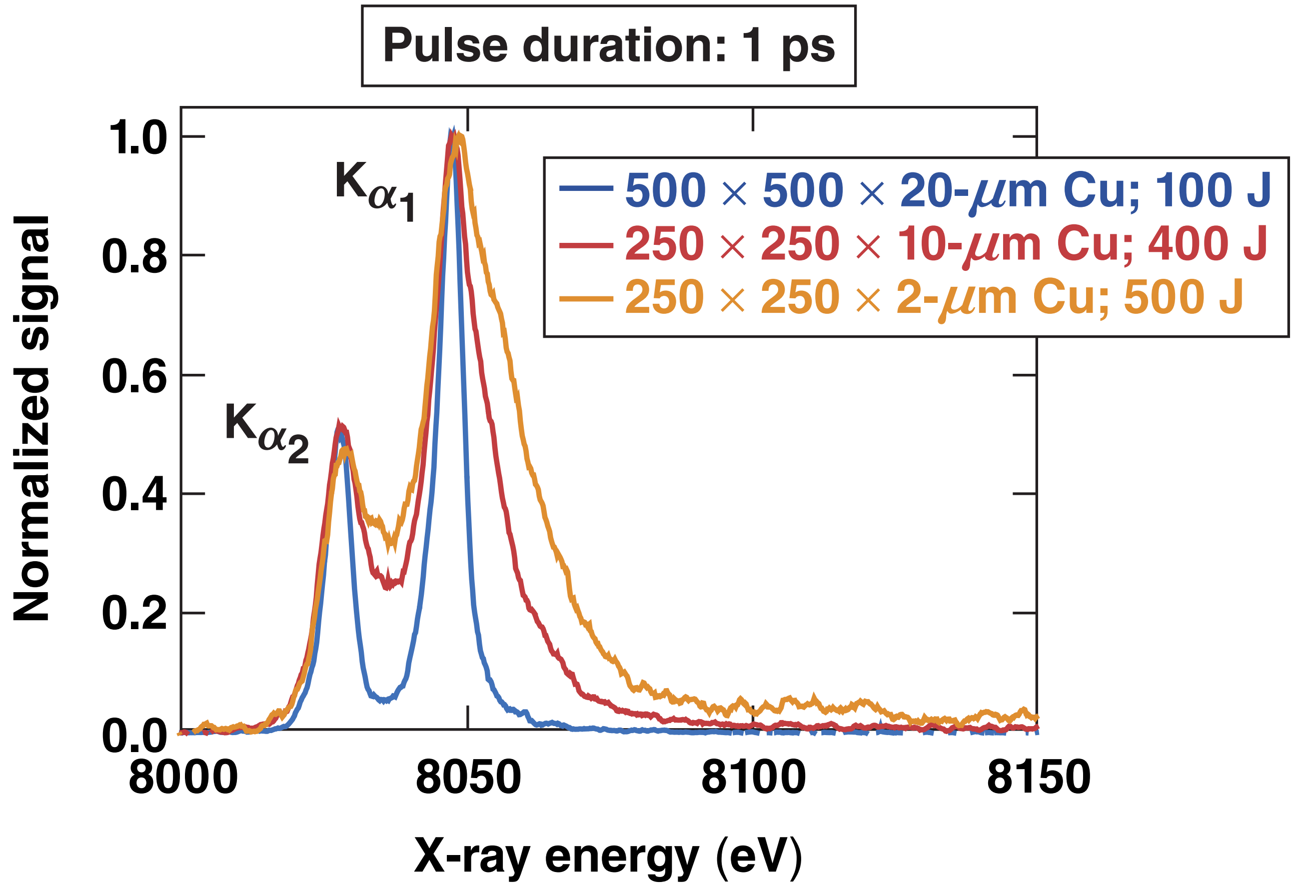
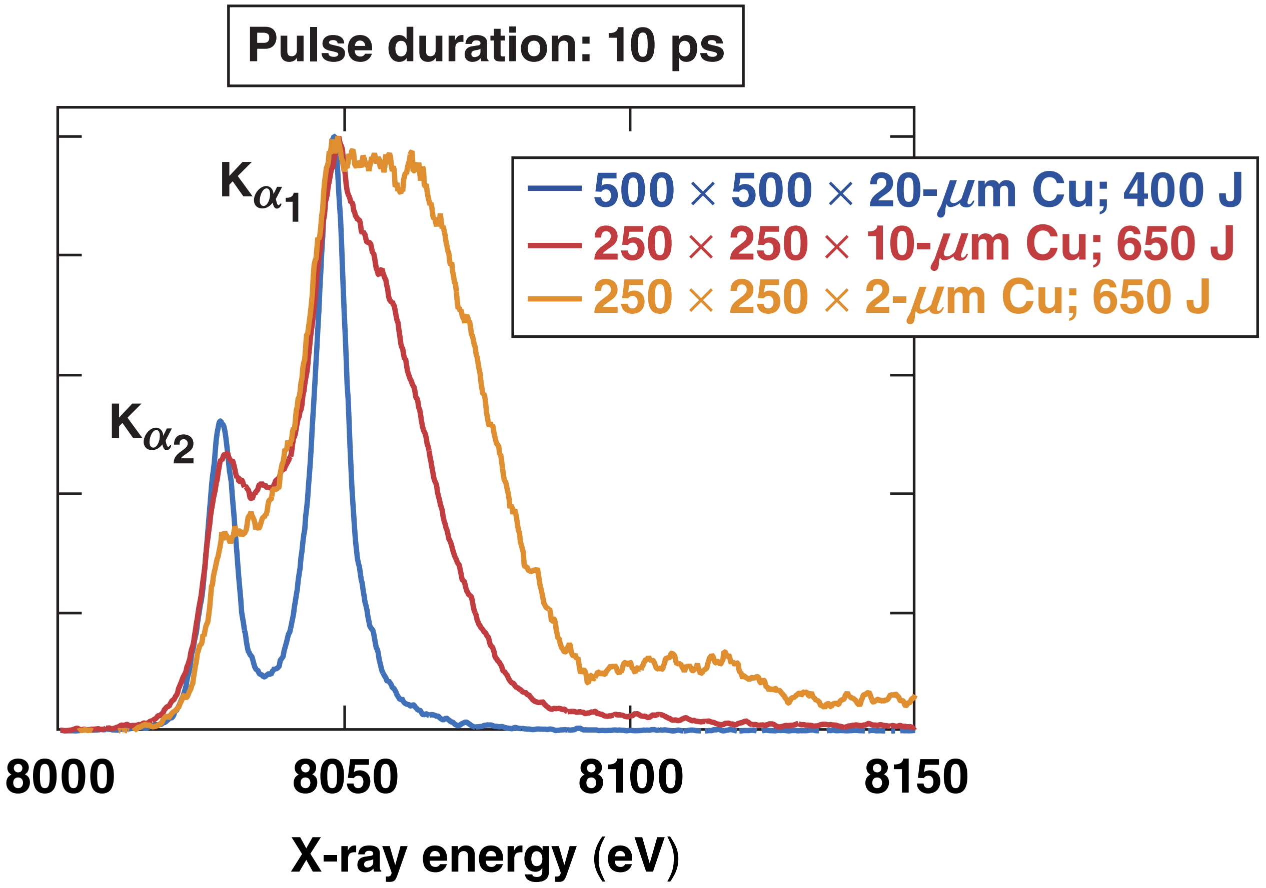
Spectrometer Measurements

Time-integrated measurements on OMEGA EP show spectral shifts increasing with target energy density





Summary/Conclusions

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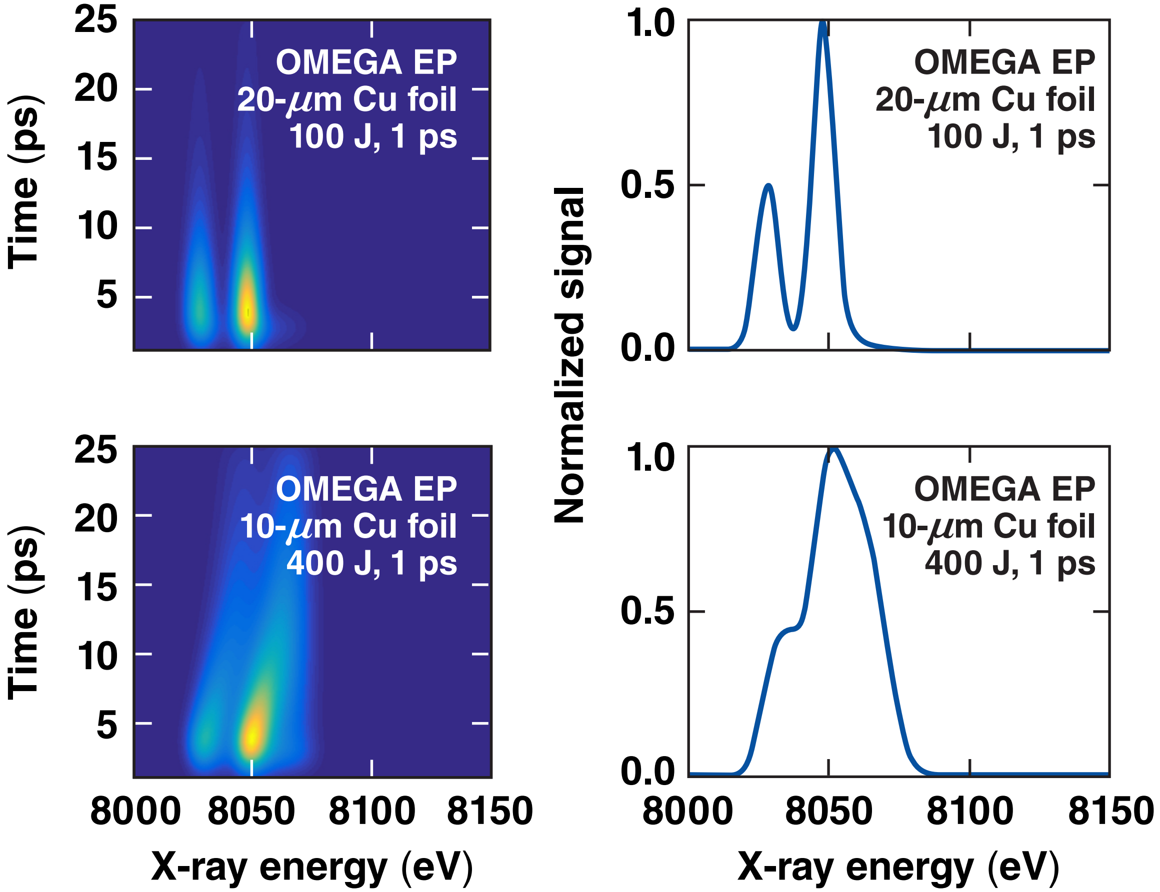
Model Predictions

Temporal spectral shifts on the Cu K_α line in rapidly heated solid matter will validate the spectrometer performance

- Synthetic spectra from hot, dense matter are required
- *LSP*[1] calculates
  - – energy-transport physics
  - – electromagnetic-field generation
  - – target heating
- *LSP* is post-processed based on tabulated *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]



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[2] Prism Computational Sciences Inc., Madison, WI 53711.
[3] D. G. Hummer and D. Mihalas, Astrophys. J. 331, 794 (1988).
[4] R. M. More, J. Quant. Spectrosc. Radiat. Transf. 27, 345 (1982).