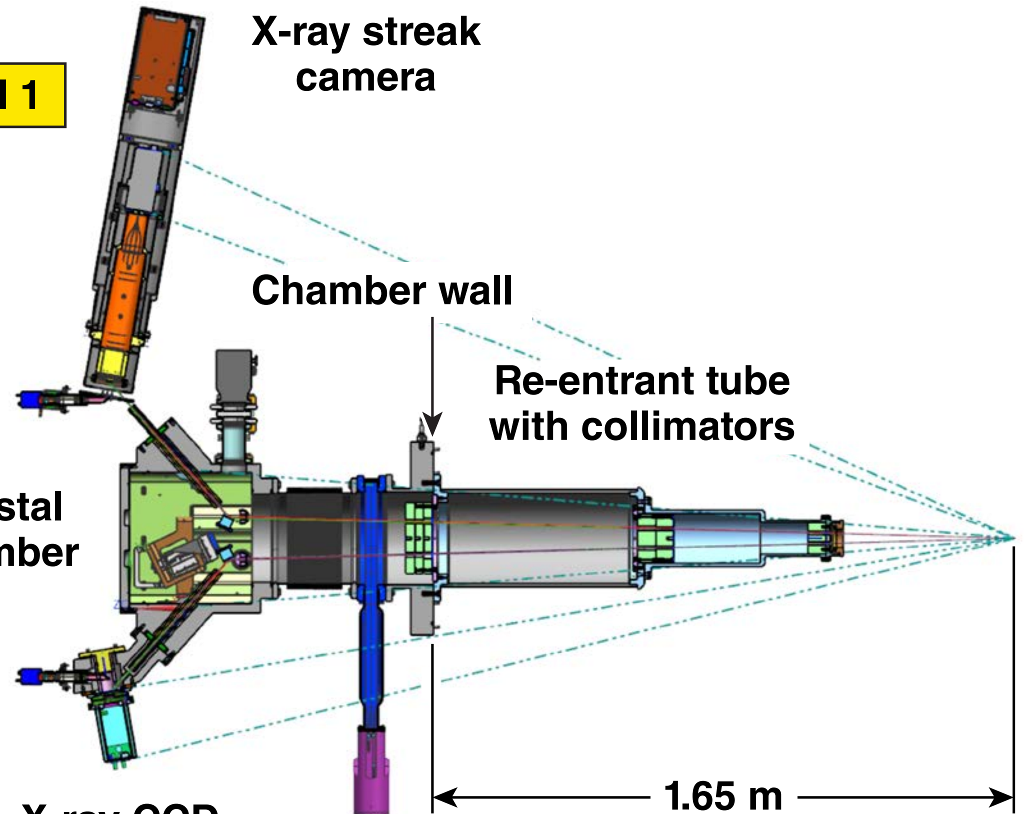
High-Resolving-Power, Ultrafast Streaked X-Ray Spectroscopy on OMEGA EP



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CEA–NNSA Joint Diagnostic Meeting
Rochester, NY
29–30 June 2016

Summary

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

- The instrument will ultimately be used to measure temperature-equilibration dynamics and material response to ultrafast heating at depth
- The goal is to achieve a resolving power of several thousand and 2-ps temporal resolution
- 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
  - several thousand resolving power
  - 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

Development is underway to deploy the time-resolved instrument on OMEGA EP by Q2FY17.

E25274b

Collaborators

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Outline

- Motivation
  - temperature-equilibration dynamics
  - material response to ultrafast heating at depth
- Conceptual design
  - high-resolution spectrometer (HiResSpec)
- Phase I
  - time-integrating x-ray spectrometer
- Phase II
  - time-resolved x-ray spectrometer

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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

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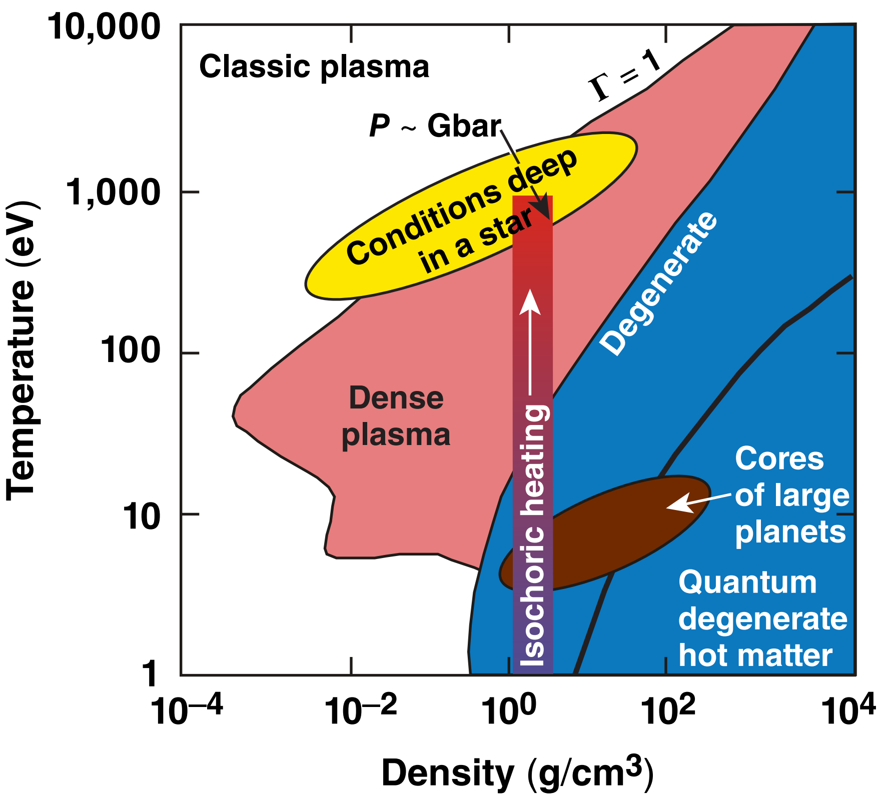
- Heating at high density produces exotic states of matter in extreme thermodynamic conditions[1]
- The possible extremes in temperature enables novel material and radiative properties experiments[2]
  - e.g., mean opacity of solar interior matter[3]
- New diagnostic techniques are sought for testing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



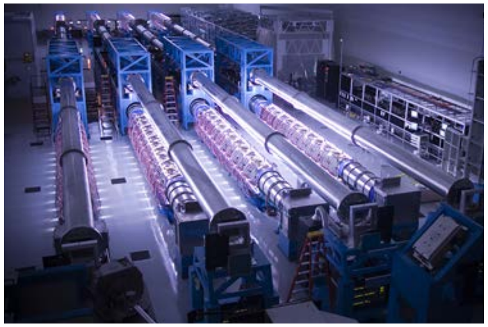
These studies require dense, high-temperature plasmas that are well characterized.

[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).

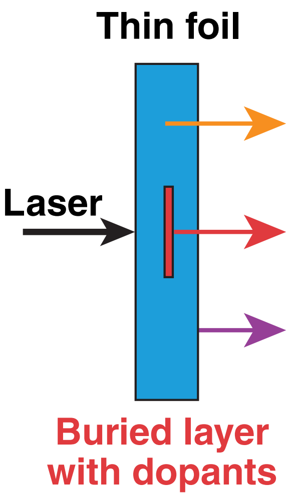
E21173h

An experimental platform is being developed to study heating of dense matter by laser-generated hot electrons

Multi-Terawatt (MTW) Laser: 10 J, 1 ps
Frequency: 1ω or 2ω
Intensity: >10^{18} W/cm^2



OMEGA EP Laser System: 2.6 kJ, 10 ps
Frequency: 1ω
Intensity: >10^{18} W/cm^2



- Source and coupling: K-line emission
  PI's—P. Nilson (LLE)/K. Hill (PPPL)
  - laser-to-electron coupling[1] $\eta_{L\text{-}e}$
  - mean hot-electron energy[2] $\langle E \rangle$
  - relaxation rate[3] τ_e
  - ionization distribution $\langle Z \rangle$
- Bulk response: thermal emission
  PI—C. Stillman (Ph.D. student, DOE SSGF)
  - Al, Fe, and Mg spectroscopy
  - density and temperature: n_e, T_e
- Surface response: XUV emission
  PI—S. Ivancic (Postdoc, DOE/FES Grant)
  - heat flow and pressure relaxation
  - density and temperature: n_e, T_e

PI: Principal Investigator
DOE SSGF: Department of Energy Stewardship Science Graduate Fellowship
DOE/FES: Department of Energy/Fusion Energy Science
PPPL: Princeton Plasma Physics Laboratory
XUV: extreme ultraviolet

[1] P. M. Nilson *et al*., Phys. Rev. Lett. 105, 235001 (2010).
[2] P. M. Nilson *et al*., Phys. Rev. Lett. 108, 085002 (2012).
[3] P. M. Nilson *et al*., J. Phys. B 48, 224001 (2015).

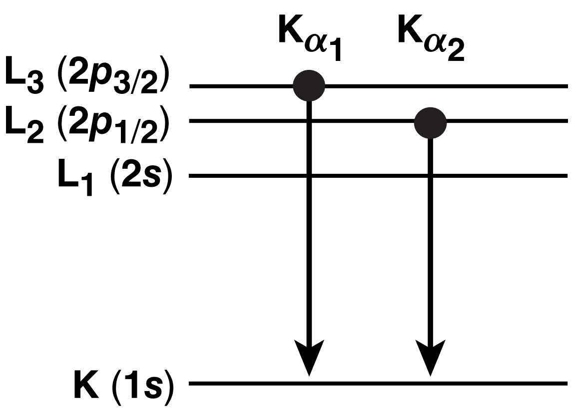
E25090c

Motivation

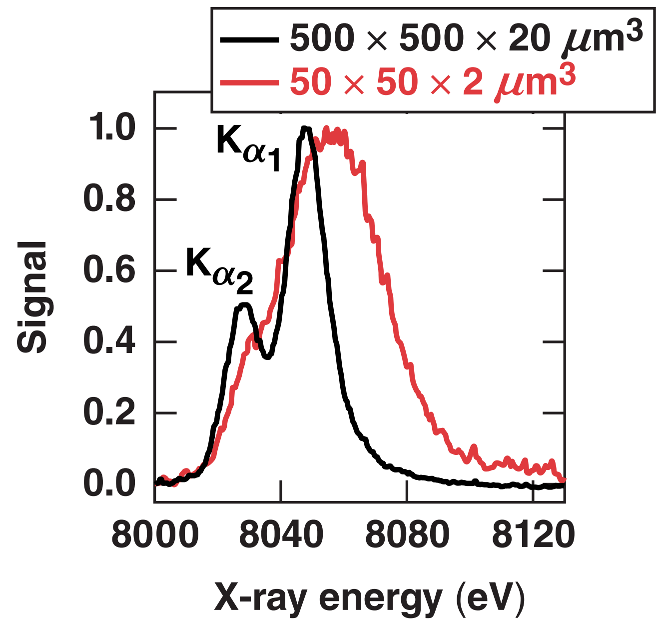
Outer shell ionization affects the energy and shape of the characteristic K_α line in a partially ionized plasma

- 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

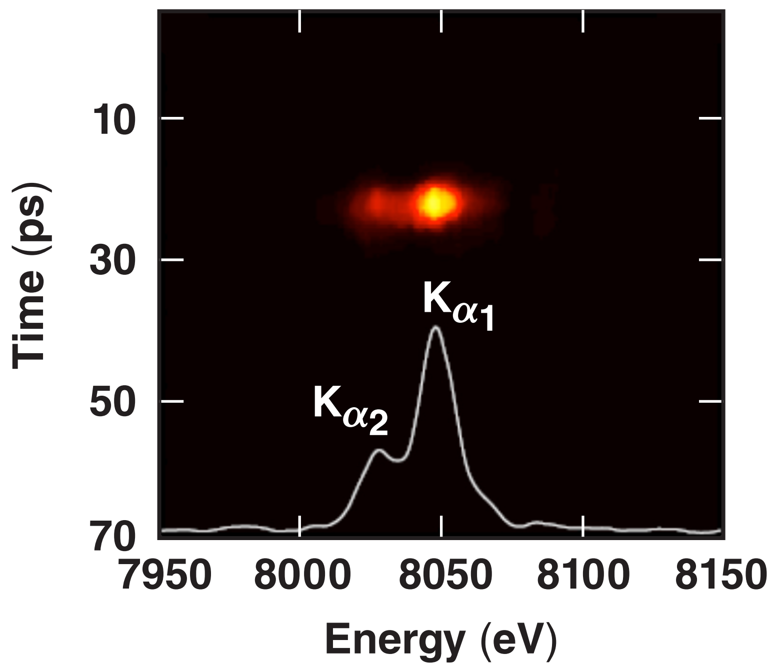


The transition energies are sensitive to the configuration of bound electrons.

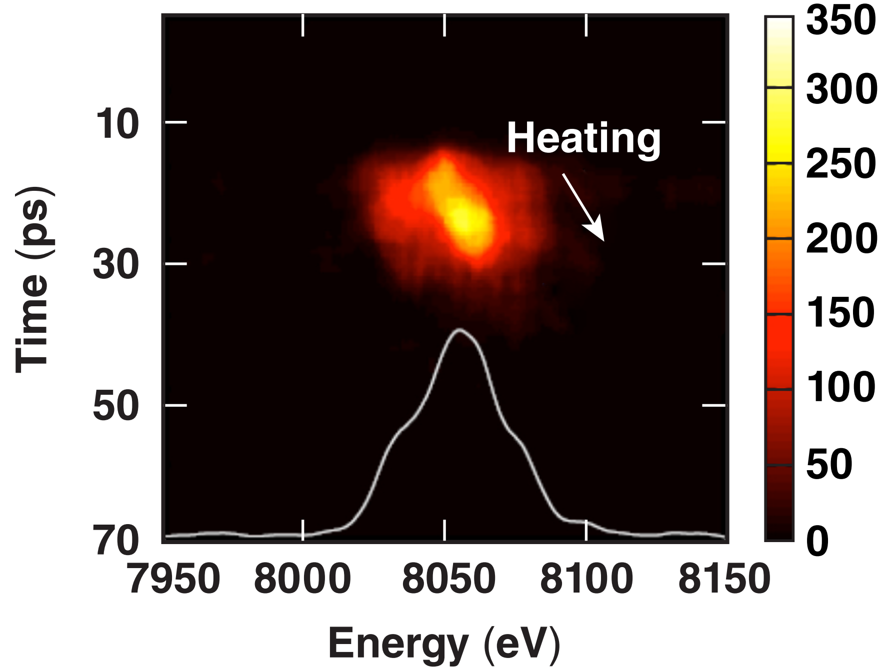
[1]K. Słabkowska *et al.*, High Energy Density Phys. 15, 8 (2015).
[2]K. Słabkowska *et al.*, High Energy Density Phys. 14, 30 (2015).
[3]G. Gregori *et al.*, Contrib. Plasma Physics 45, 284 (2005).
[4]P. M. Nilson *et al.*, Phys. Plasmas 18, 042702 (2011).
[5]J. F. Seely *et al.*, High Energy Density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

E18508c

Survey experiments on the MTW laser have demonstrated temporal spectral shifts on the Cu K_{α} line



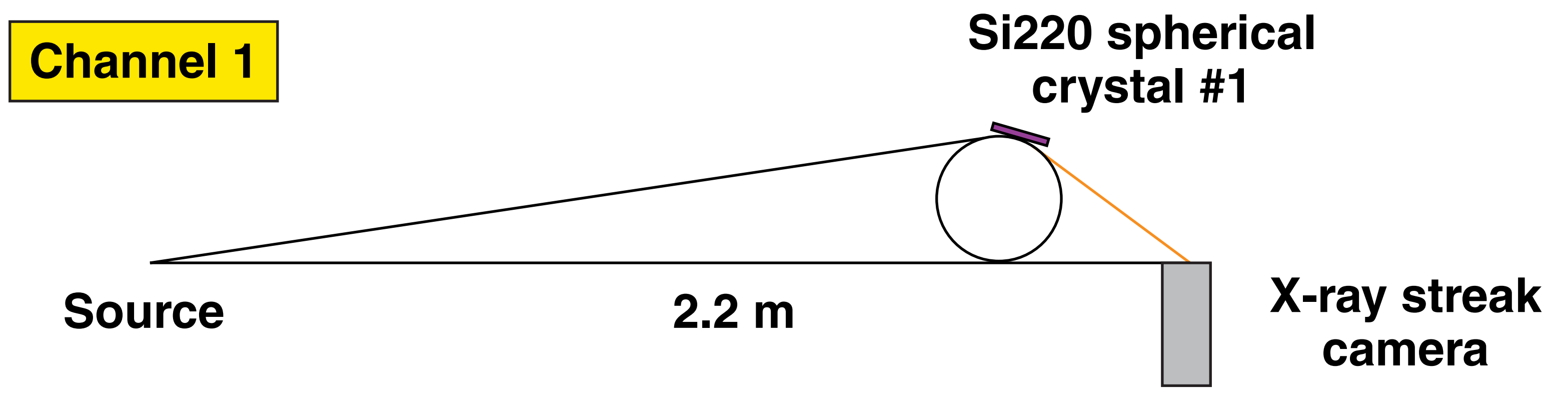
Shot 5708: 1 J, 0.8 ps
500 × 500 × 20 μm Cu

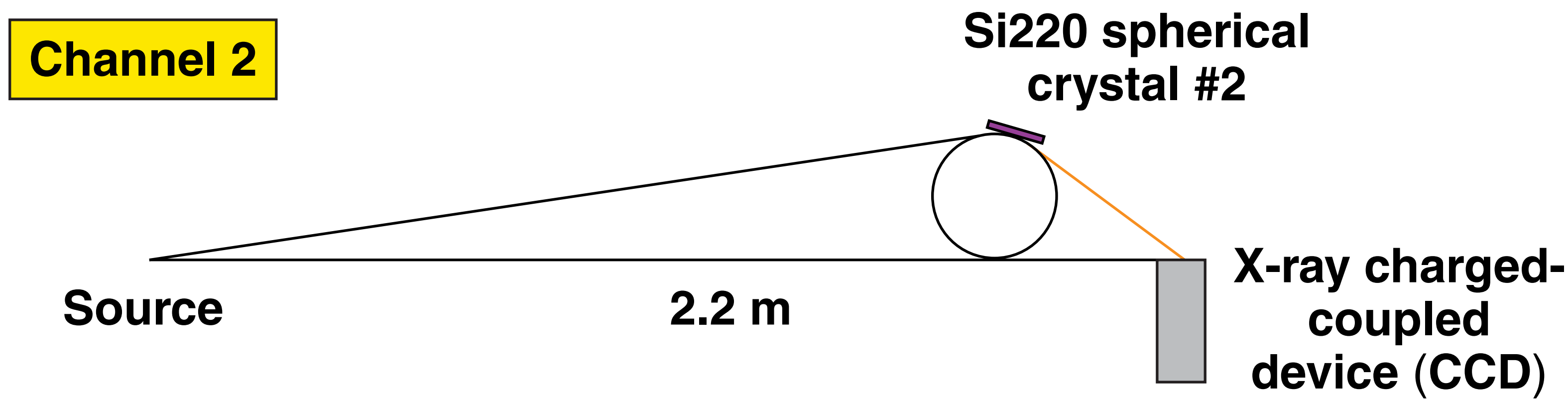


Shot 5698: 10 J, 7 ps
60 × 60 × 2 μm Cu

Higher ionization and excited states are populated as the plasma heats.

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





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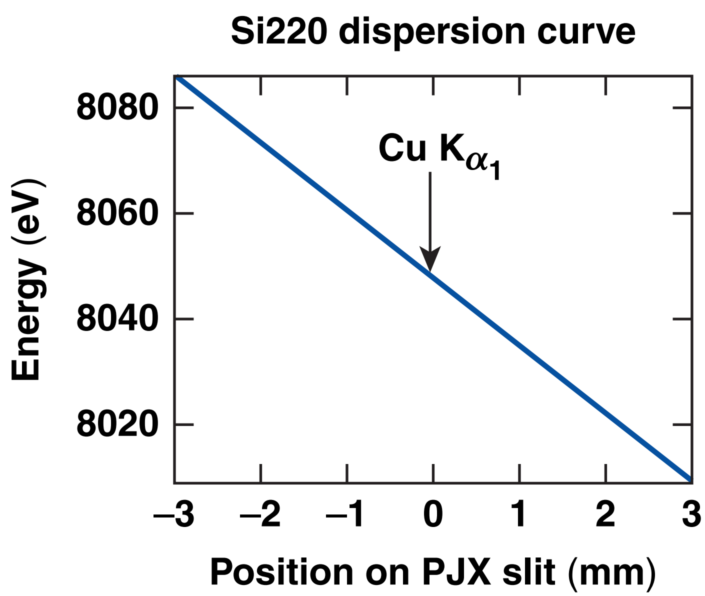
The instrument parameters are set by the expected Cu K_α line shifts

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



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Survey Spectrometer

The Phase I spectrometer was deployed in January 2016 on OMEGA EP for experiments and diagnostic development

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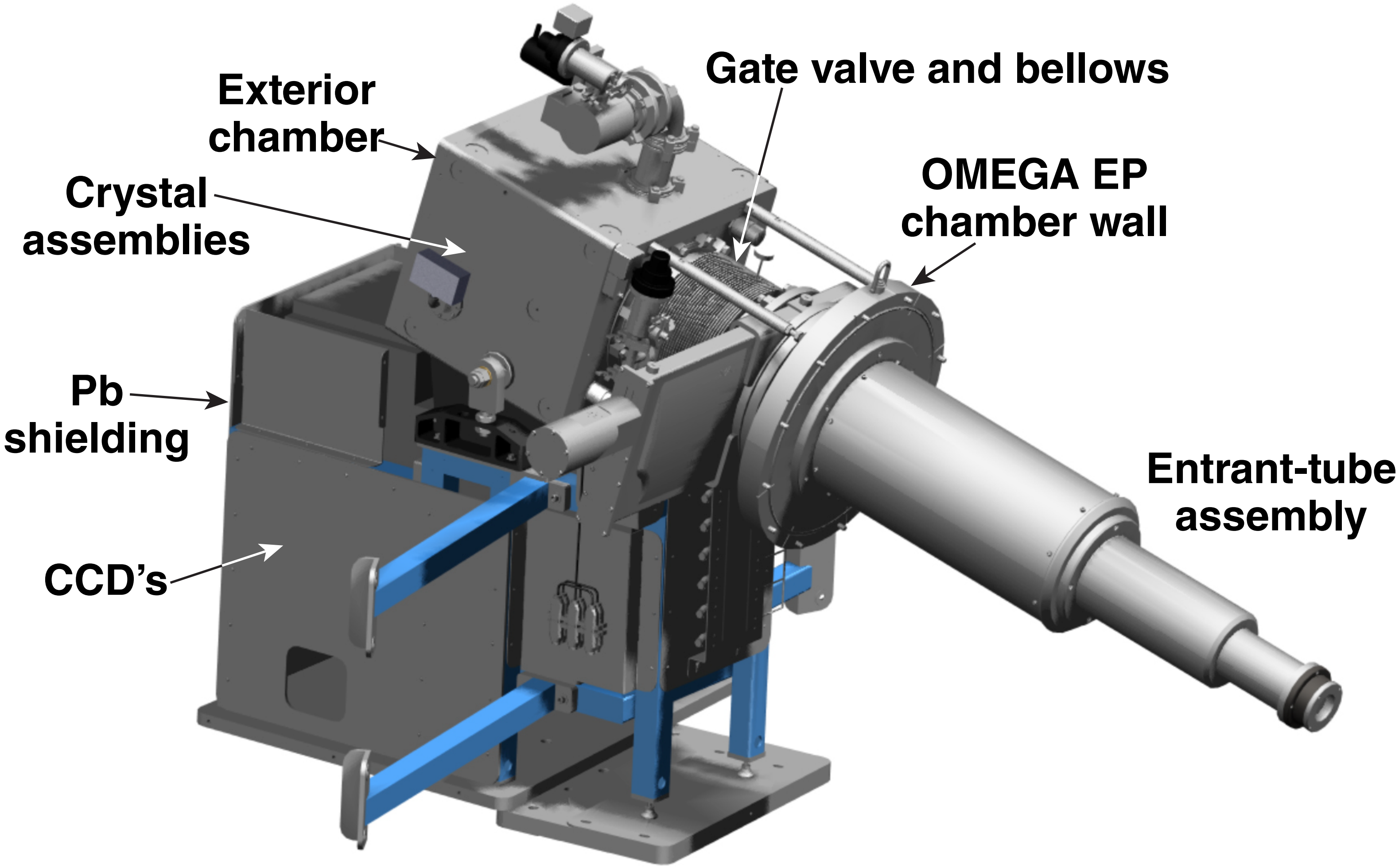
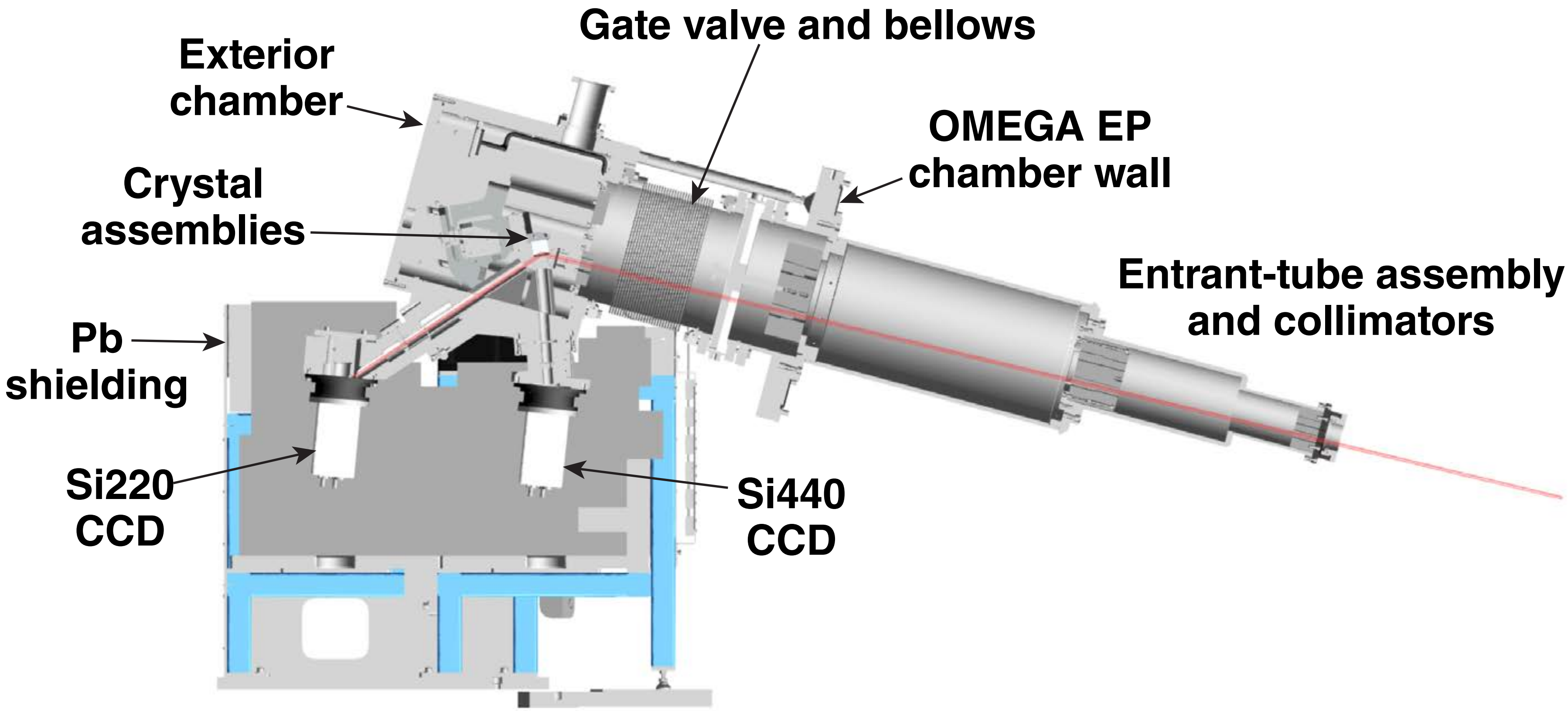


Deck 2 modifications

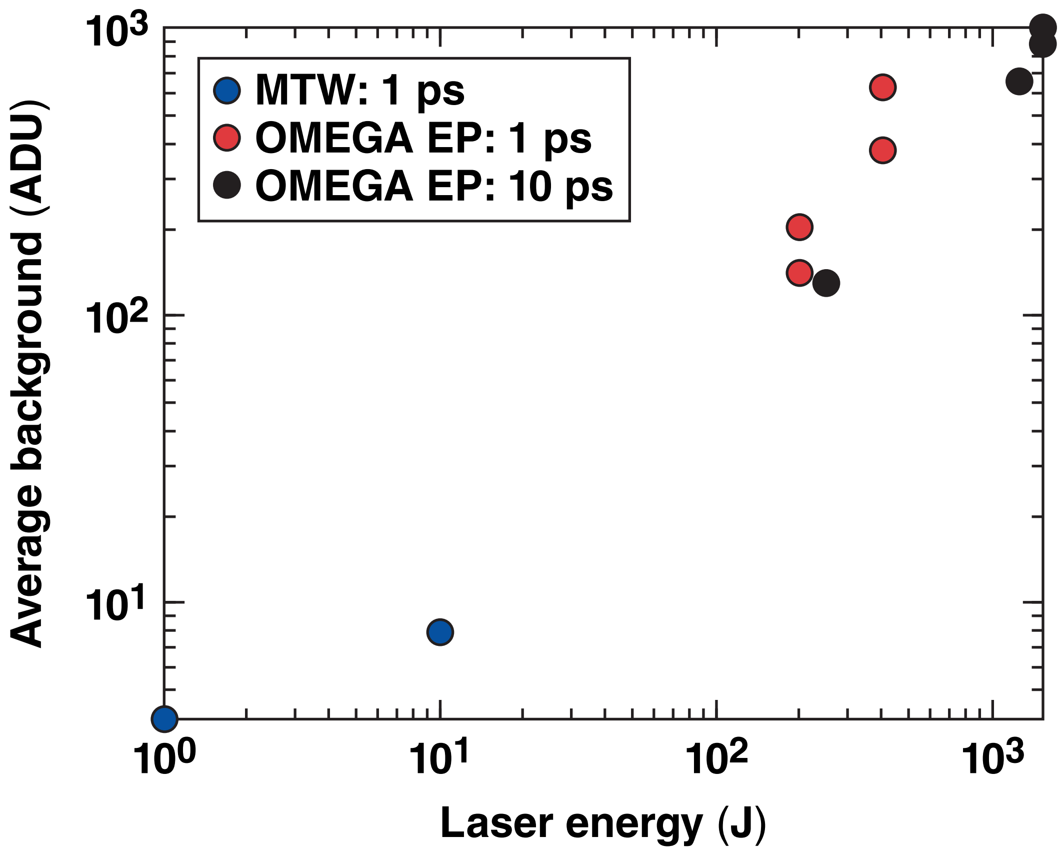
E25094b

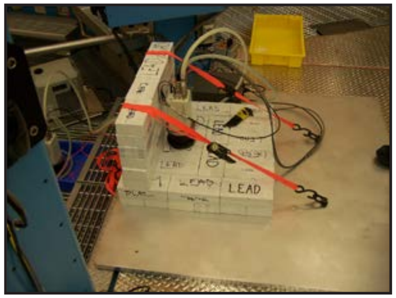
The Phase I spectrometer was deployed in January 2016 on OMEGA EP for experiments and diagnostic development



E25095b

OMEGA EP data show average background signals per pixel of up to 1000 ADU at 1.65 m from the source





A 5-cm direct line-of-sight lead shielding reduced the background to ~50 ADU.

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Inrad Optics manufactured the crystal assemblies

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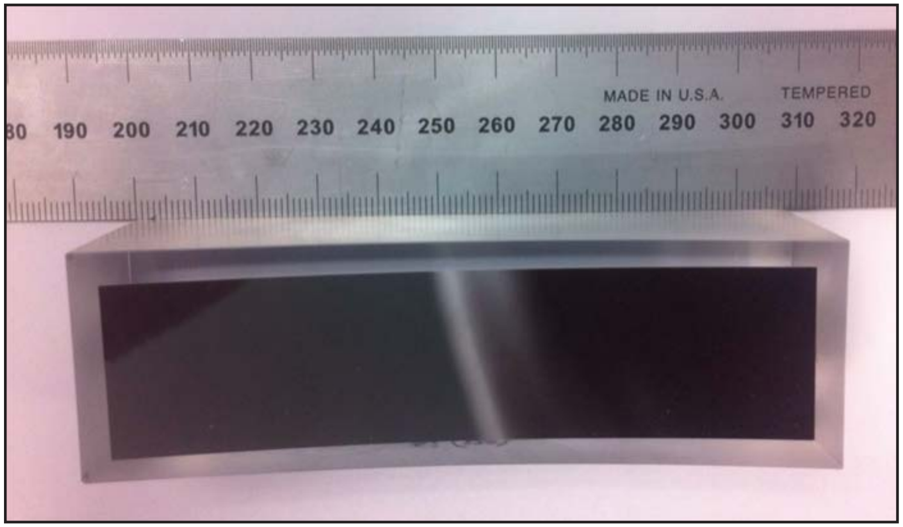
100 mm



- The silicon crystal is 100 μm thick and 25 mm × 100 mm in size
- The crystal is optically bound to a glass substrate that is shaped to a radius of R = 330 mm

E23450a

The focusing properties and resolving power of the OMEGA EP crystal were measured

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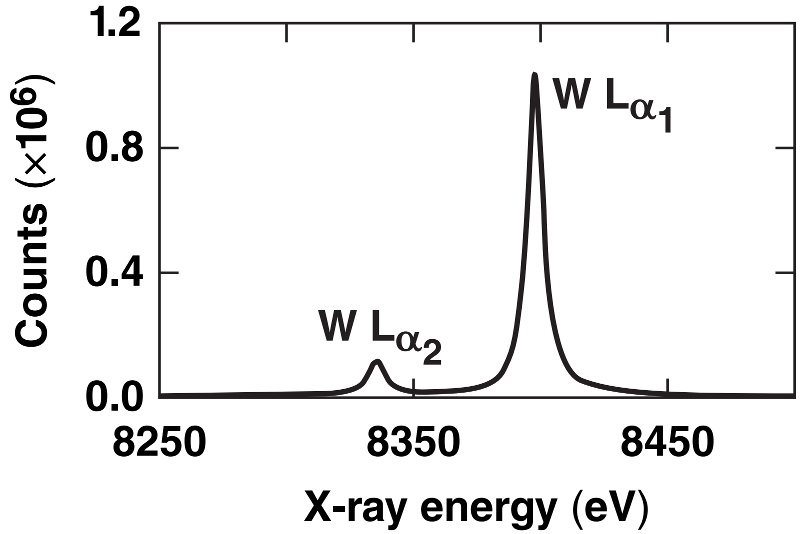
PRINCETON UNIVERSITY

- W L_{α_1} line width at 8.3976 keV agrees with the estimated line width of ~7 eV plus the additive width caused by the finite rocking curve width of ~0.48 eV*
- The measured line width did not change as the crystal was masked—the curvature is good

Pilatus detector: 172-μm pixel size



*A.-M. Vlaicu *et al*., Phys. Rev. A 58, 3544 (1998).

High-power experiments show excellent focusing fidelity, resolving power, and throughput

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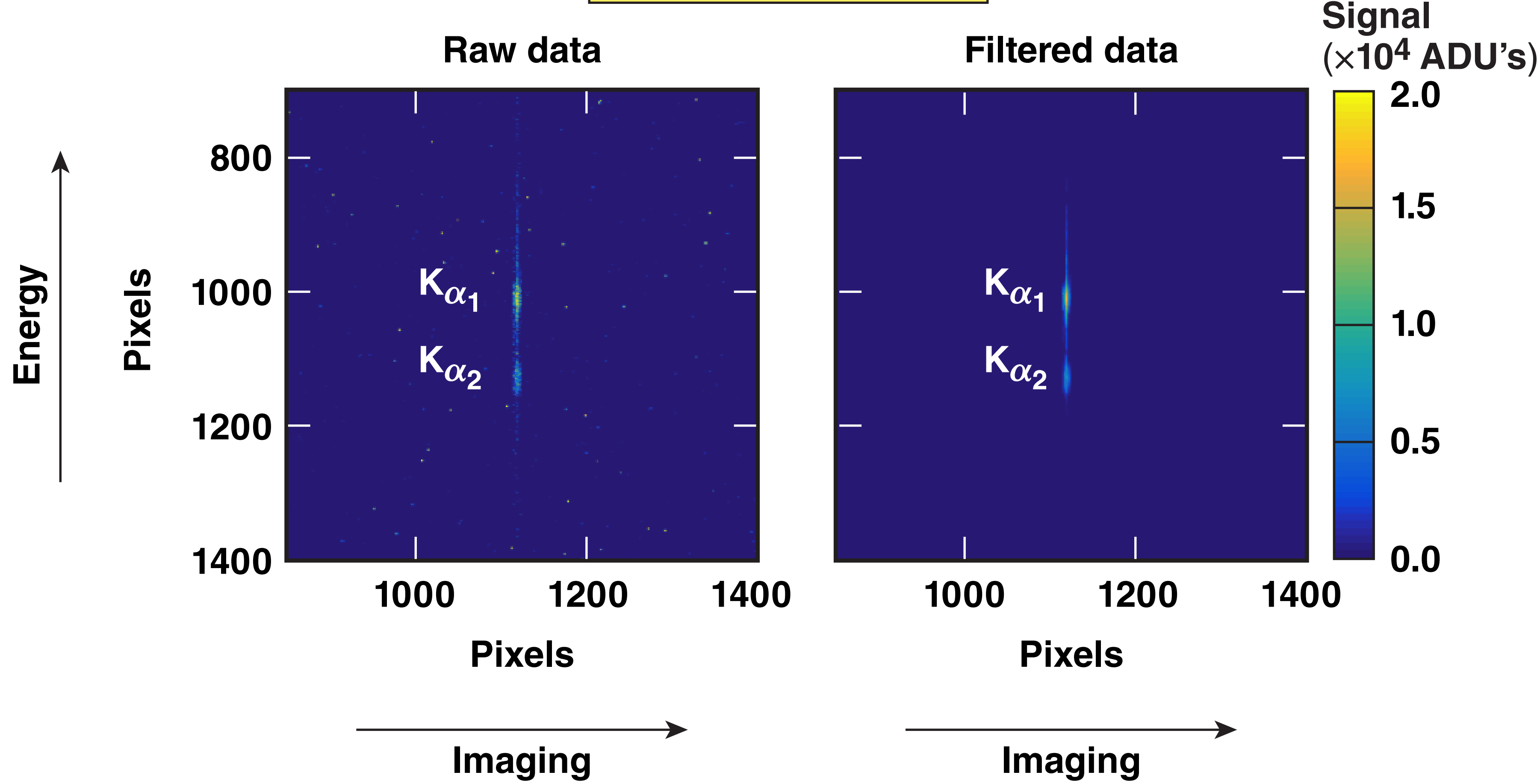
Shot 22854
100 J, 1 ps—Si220



E25096

The Si220 throughput will provide a measurable signal on the PJX-3 streak camera

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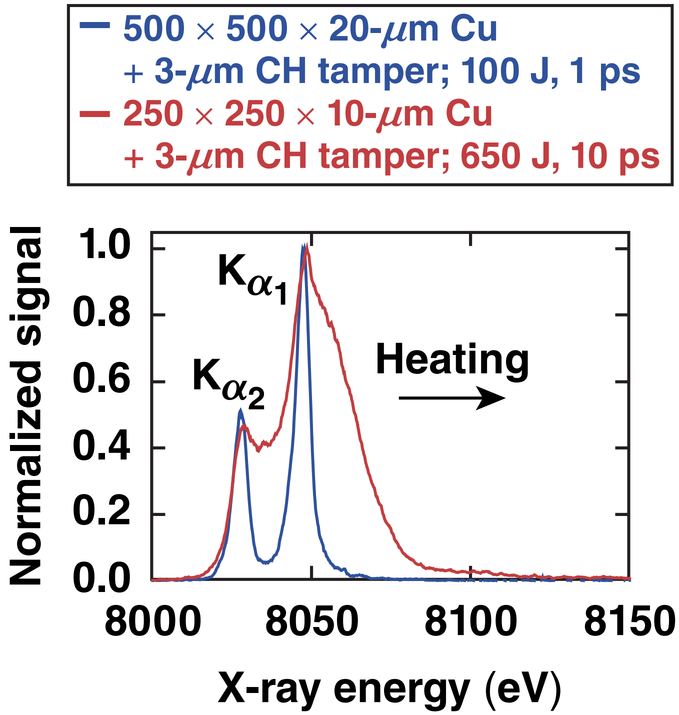
- The measured throughput is 1.4×10^{-7} ph/ph
- The predicted peak signal at the streak camera is ~1000 ADU per pixel
- Photometric estimates are based on
  - laser energy: 100 J
  - x-ray flash duration: 10 ps
- Shifted spectra are well-matched to the length of the streak-camera slit



Phase I has provided the foundation for designing and implementing the time-resolved instrument.

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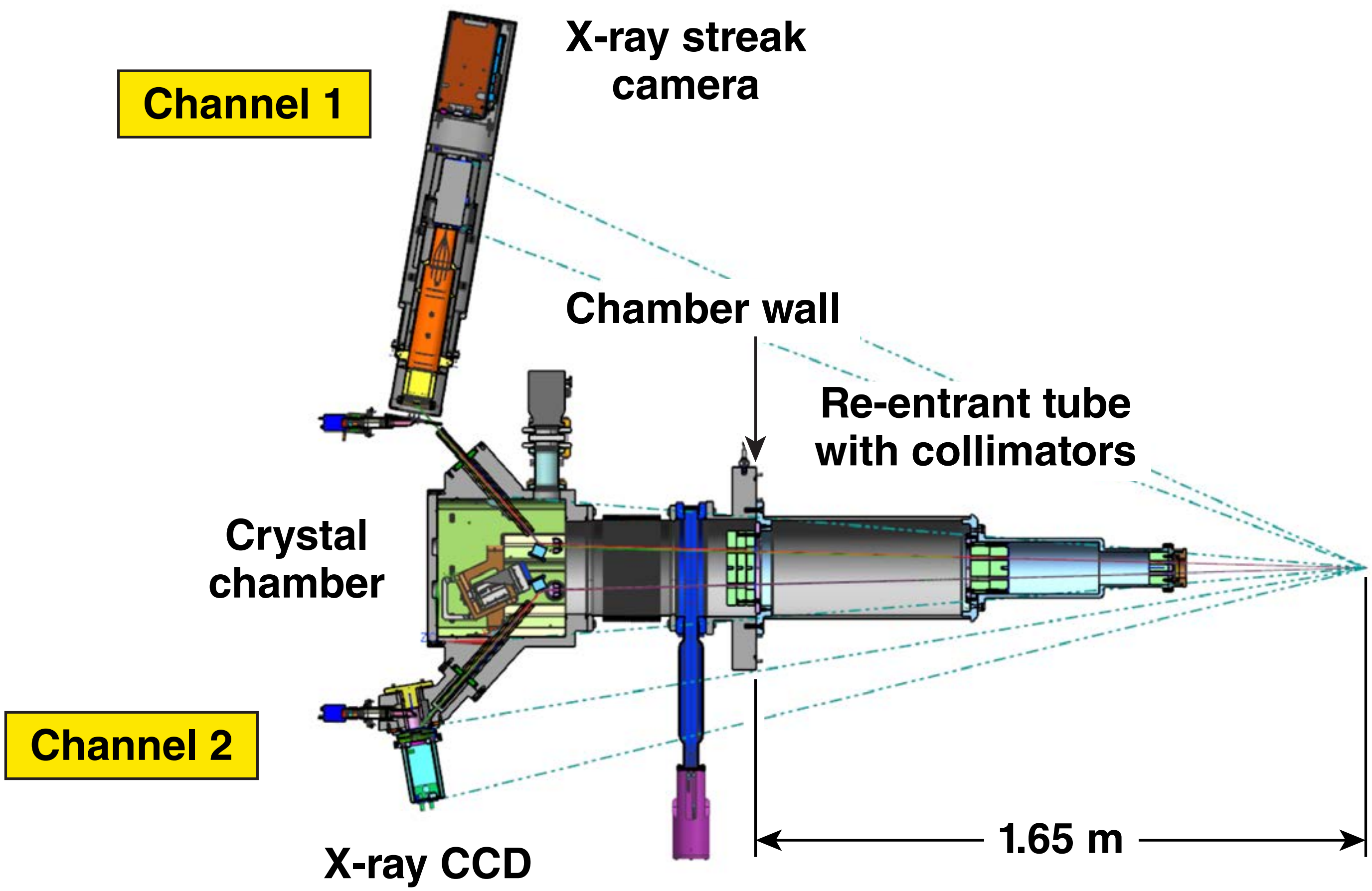
The Phase II instrument adds a second crystal assembly and the PJX-3 x-ray streak camera for time-resolved measurements



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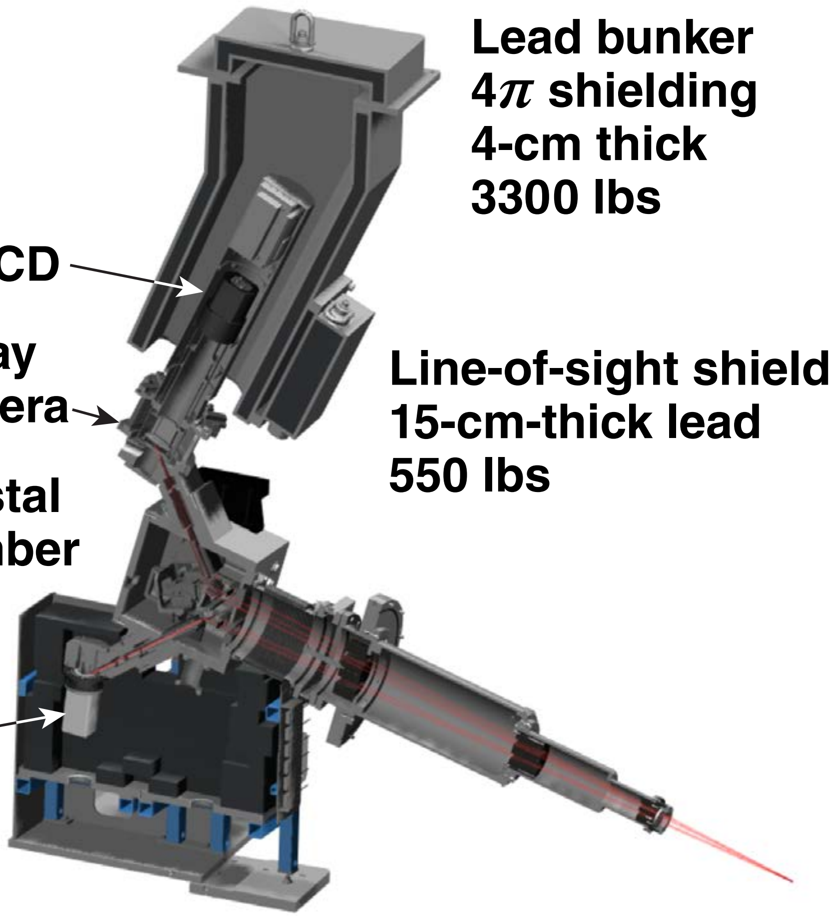
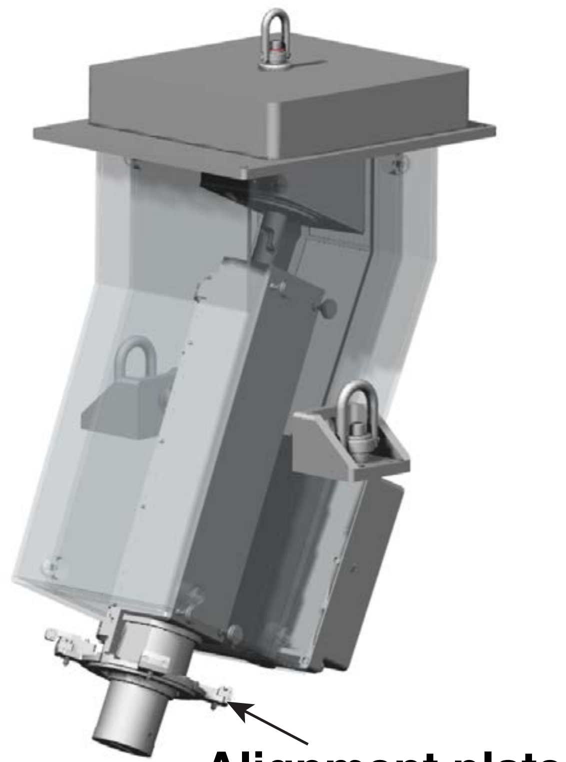
Mechanical Design

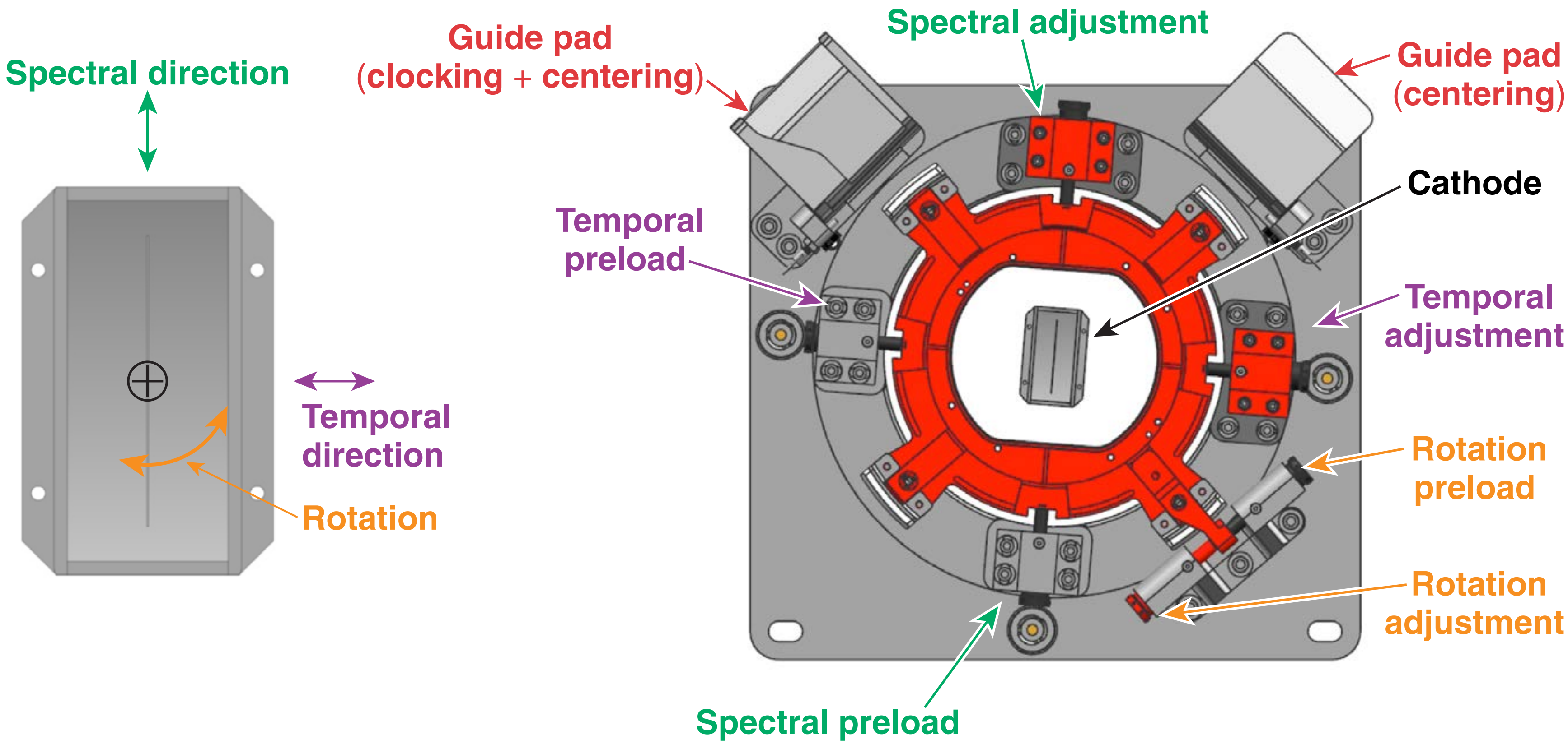
Significant shielding assemblies are required for the x-ray streak camera





E25098

Fine adjust along four degrees of freedom is provided near the PJX-3 cathode*



HiResSpec will be deployed in Q2FY17 for commissioning and first high-power shots.

*For detailed tolerance analysis, see D-HS-R-121 Rev A (March 2015).

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

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  - throughput: ~10^{-7} ph/ph
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- These measurements provide a firm foundation for designing and implementing the time-resolved instrument

Development is underway to deploy the time-resolved instrument on OMEGA EP by Q2FY17.

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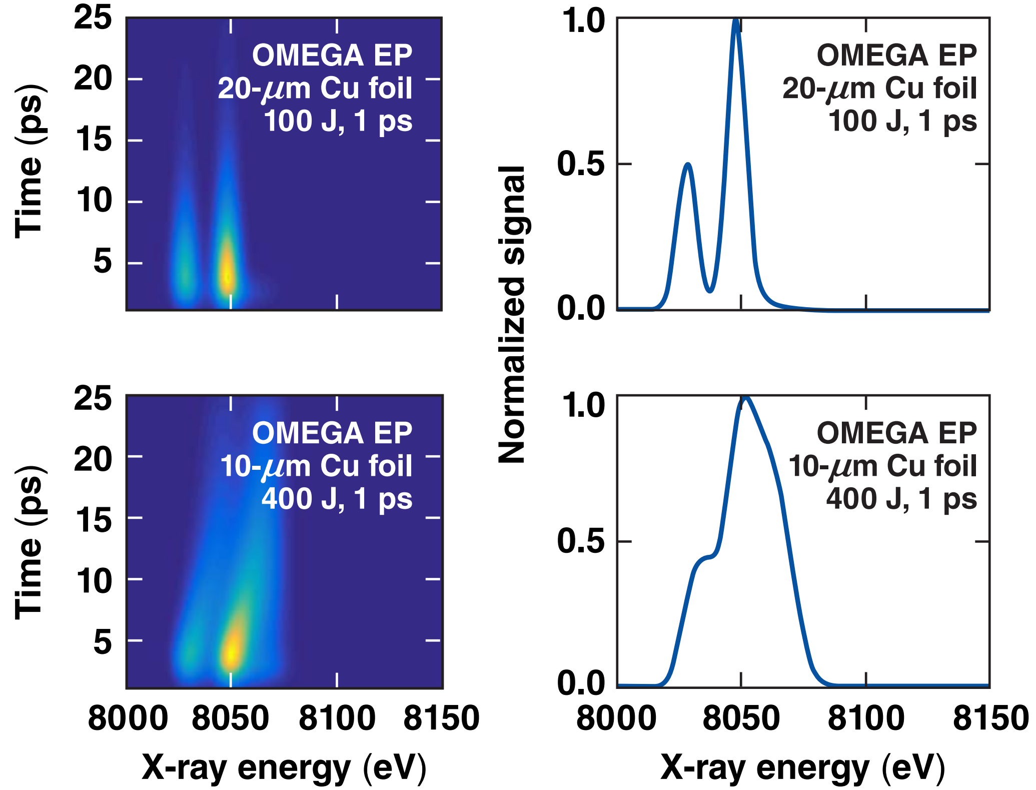
Model Update

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

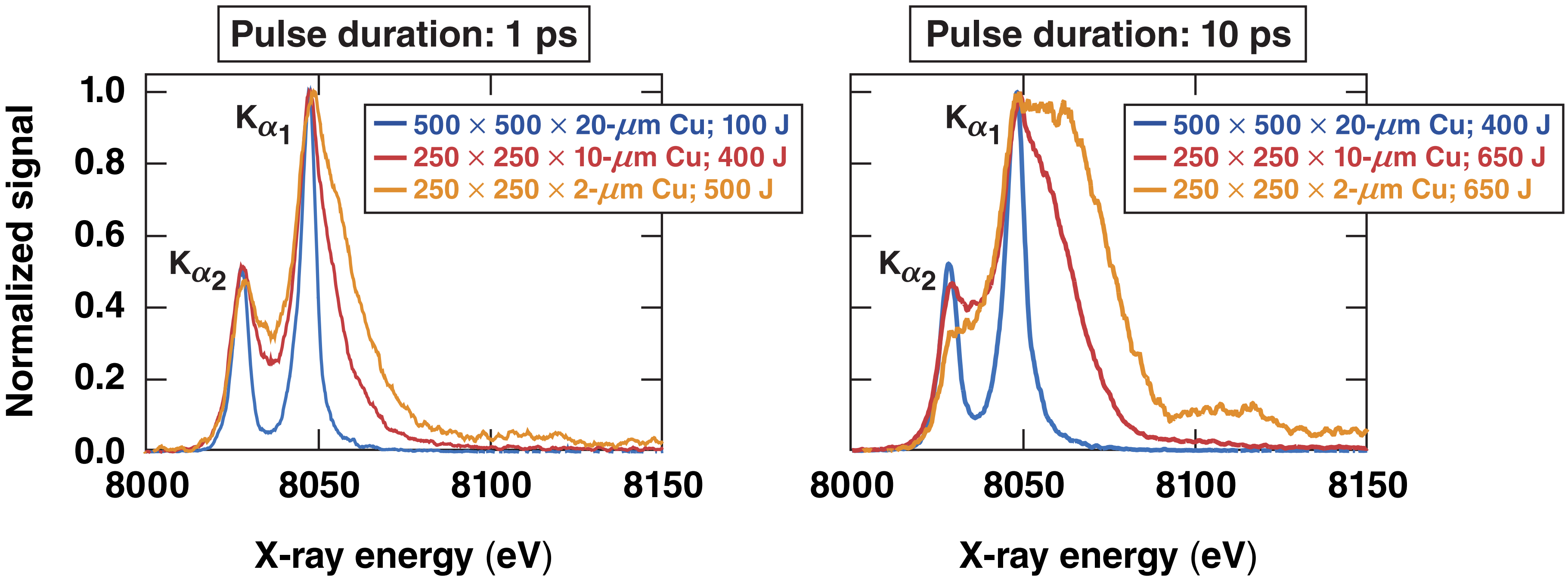
- Synthetic spectra from hot, dense matter are required
- *LSP*[1] calculates
  - energy-transport physics
  - electromagnetic-field generation
  - target heating
- *LSP* is post-processed based on tabulated *PrismSPECT*[2] calculations using
  - the local density and temperature at the time of emission
  - 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]



[1]D. R. Welch *et al*., Phys. Plasmas 13, 063105 (2006).
[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).

E25130c

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



The dispersed x-ray signals are well-matched to the length of the x-ray streak-camera slit.

E25203b